
Proceedings of:

Coordinate Measuring Machines

2003 Summer Topical Meeting

June 25 and 26, 2003

*C. C. Cameron Applied Research Center
University of North Carolina
Charlotte, North Carolina*

The American Society for Precision Engineering (ASPE) is a multidisciplinary professional and technical society concerned with research and development, design, manufacture and measurement of high accuracy components and systems. ASPE activities encompass relevant aspects of mechanical, electronic, optical and production engineering, physics, chemistry, and computer and materials science. Membership is open to anyone interested in any aspect of precision engineering.

Founded in 1986, ASPE provides a new focus for a diverse but important community. Other professional organizations have covered aspects of precision engineering, always as a sideline to their principal goals. ASPE is based on the core of generic concepts necessary to achieve precision in any application; independent of discipline, ASPE intends to be the focus for precision technology - and to represent all facets from research to application.

*ASPE -- The American Society for Precision Engineering
301 Glenwood Avenue, Suite 205, Raleigh, NC 27603
P.O. Box 10826, Raleigh, NC 27605
Telephone: (919) 839-8444 Fax (919) 839-8039
Web site: <http://www.aspe.net>*

Preface

This book comprises the proceedings of the 2003 Summer Topical Meeting. The contributions reflect the authors' opinions and are published as presented to ASPE, without change. Their inclusion in this publication does not necessarily constitute endorsement by the ASPE, or its editorial staff.

Individual readers of this book and nonprofit libraries acting for them are permitted to make fair use of the material contained in this book to be used in teaching or research; provided they copy said paper in total, as written by the author. Permission is granted to quote excerpts from the scientific or technical works in this book with proper acknowledgment of the source to include: The author's name, the book name, and the ASPE tag line. Reproduction of figures and tables is likewise permitted from the contents of this book, provided that the same acknowledgment of the same source and content is permitted.

Any other type reproduction, systematic copying or multiple reproduction of any material in this book is expressly prohibited except with the written permission of the ASPE editorial staff, addressed to the Society's headquarters.

ISBN 1-887706-31-3

2003

American Society for Precision Engineering
301 Glenwood Avenue, Suite 205
Raleigh, NC 27603

Printed in the United States of America

2003 Summer Topical Meeting

Contents

<i>Preface.....</i>	<i>ii</i>
<i>Contents.....</i>	<i>iii</i>
<i>Program.....</i>	<i>iv</i>
<i>Foreword.....</i>	<i>v</i>
<i>Technical Paper Index.....</i>	<i>vi</i>
<i>Technical Papers.....</i>	<i>3-93</i>
<i>Author Index.....</i>	<i>95</i>

2003 Summer Topical Meeting

Meeting Schedule

	Wednesday, June 25		Thursday, June 26
8:00	Registration & Light Breakfast	8:00	Registration & Light Breakfast
8:45	Welcome, CPM Introduction	8:30	TECHNICAL SESSION IV
9:15	TECHNICAL SESSION I		
10:35		10:30	
	Break		Break
10:55	TECHNICAL SESSION I (Continued)	10:50	TECHNICAL SESSION V
12:15		12:10	
	Lunch		Lunch
1:15	TECHNICAL SESSION II	1:10	TECHNICAL SESSION V (Continued)
2:35		1:50	TECHNICAL SESSION VI
3:15	TECHNICAL SESSION III	3:10	
	Break		Break, Wrap-up / CPM Tours
3:35	TECHNICAL SESSION III (Continued)	4:00	
5:30			
6:30	Reception		

Foreword

This meeting will focus on developments in the technology of coordinate measuring systems including both hardware and software. After decades of coordinate measurement where data on part surfaces were primarily taken a point at a time using so-called touch trigger probes, modern systems are using a variety of "probing" techniques that acquire data much more rapidly and densely. These techniques include vision (with a spectrum of illumination techniques), optical triangulation, mechanical scanning, and other emerging techniques ranging from tomography to atomic force microscopy.

All of these techniques yield much larger data sets than previously, require different algorithms for data reduction, and present unique metrological challenges. In addition to these factors, a larger number of parts that have tolerances in the sub-micron domain are being produced which is placing increasing demands on the accuracy of these measuring systems. Integration of the new hardware and software into new measurement systems that conform to ISO 9000 is also an issue as the uncertainties of these complex systems are difficult to estimate.

The object of this meeting is to bring together researchers and practitioners from industry, government and academia to provide a forum for the exchange of ideas. It is anticipated that this subject will attract participants who are not currently active in the ASPE. We encourage the attendance of non-ASPE members and look forward to their contribution.

2003 Summer Topical Meeting Co-Chairmen:
Robert J. Hocken, Gregory W. Caskey, and Edward P. Morse
University of North Carolina at Charlotte

Technical Paper Index

Wednesday, June 25, 8:45 a.m. – 9:15 a.m.

Welcome, CPM Introduction

Robert J. Hocken (University of North Carolina at Charlotte)

Session I

Calibration/Performance Assessment

Wednesday, June 25, 9:15 a.m. – 12:15 p.m.

1. **Using a CMM for Optical System Assembly and Alignment** 3
Parks, R. E.; Kuhn, W. P. (Optical Perspectives Group, LLC)
2. **Proposed New Tests for Evaluating CMM Performance** 9
Pereira, P. H.; Beutel, D. E. (Caterpillar, Inc.)
3. **New Concept Geostep** 15
Gleason Jr., E. A. (Ball Tech)
4. **Six Degree of Freedom Precision Measurement System** 17
Cui, H.; Pan, Z.; Zhu, Z. (Stevens Institute of Technology)

Session II

Software/Algorithms

Wednesday, June 25, 1:15 p.m. – 2:35 p.m.

1. **Evaluation of CMM Tolerance Calculation Software** 21
Thomas, P. D. (Mitutoyo America Corporation)
2. **An Improved B-spline Approach for the Surfaces Reconstruction from Data Measured by CMM** 26
Caliò, F.; Miglio, E.; Moroni, G.; Rasella, M. (Politecnico di Milano)

Session III

CMM Design

Wednesday, June 25, 2:35 p.m. – 5:30 p.m.

1. **A Novel Ultra Precision CMM Based on Fundamental Design Principles** 33
Ruijl, T. A. M. (Philips Centre for Industrial Technology); and van Eijk, J. (Delft University of Technology)
2. **Design of a 3D-Coordinate Measuring Machine for Measuring Small Products in Array** 39
van Seggelen, J. K.; Rosielle, P. C. J. N.; Schellekens, P. H. J. (Eindhoven University of Technology); and Spaan, H. A. M. (IBS Precision Engineering bv); and Bergmans, R. H. (NMI Van Swinden Laboratorium)
3. **A Modular, Multiple Sensor Embedded System CMM Motion Controller** 43
Chang, D. W.; Wu, P.; Harris, J. O.; Spence, A. D. (McMaster University); and Peterson, J. E.; Heslip, J. (Omni-Tech Corporation)
4. **Russ Shelton: Father of the CMM (Invited Paper)** 49
Devitt, A. J. (New Way Precision)

Session IV

Uncertainty Issues

Thursday, June 26, 8:30 a.m. – 10:30 a.m.

1. **The Validation of CMM Task Specific Measurement Uncertainty Software** 51
Phillips, S. D.; Borchardt, B. R.; Abackerly, A. J.; Shakarji, C.;
Sawyer, D. (National Institute of Standards and Technology); Murray, P.;
Rasnick, W. H. (BWXT Y-12, LLC); and Summerhays, K. D.; Baldwin, J. M.;
Henke, R. P.; Henke, M. P. (MetroSage, LLC)
2. **Manufacturing Signatures and CMM Sampling Strategies**..... 57
Moroni, G.; Rasella, M. (Politecnico di Milano); and Polini, W. (Università di Cassino)
3. **Calibrating and Testing CMMs in a World of Uncertainty and Accreditation** 63
Salsbury, J. G. (Mitutoyo America Corporation)

Session V

Probe Design

Thursday, June 26, 10:50 a.m. – 1:50 p.m.

1. **Novel 3D Analogue Probe With a Small Sphere and Low Measurement Force** 69
Meli, F.; Bieri, M.; Thalmann, R. (Swiss Federal Office of Metrology, METAS);
Fracheboud, M.; Breguet, J.-M.; Clavel, R. (Institut de Production et Robotique, EPFL);
and Bottinelli, S. (MECARTEX, Z.I.)
2. **A Study for Development of Small-CMM Probe Detecting Contact Angle** 74
Ogura, I.; Okazaki, Y. (National Institute of Advanced Industrial Science & Technology)
3. **A Trinocular Vision Probe for Sculptured Surface Measurements** 78
Zhang, G. X.; Zhang, H. W.; Liu, Z.; Guo, J. B.; Zhao, X. S.; Fan, Y. M.; Qiu, Z. R.;
Li, X. F.; Li, Z. (Tianjin University)

Session VI

Applications

Thursday, June 26, 1:50 p.m. – 3:10 p.m.

1. **Non-contact Shape Measurements of Ultra-lightweight X-ray Optics** 84
Hadjimichael, T.; Fleetwood, C. (Swales Aerospace); and Content, D.;
Waluschka, E.; Wright, G. (NASA Goddard Space Flight Center)
2. **High Accuracy CMM Measurements of Large Silicon Spheres** 89
Stoup, J. R.; Doiron, T. D. (National Institute of Standards and Technology)

Wrap-up and CPM Tour

Thursday, June 26, 3:10 p.m. – 4:00 p.m.

Technical Papers



A S P E

Using a CMM for optical system assembly and alignment

Robert E. Parks and William P. Kuhn
Optical Perspectives Group, LLC
Tucson, AZ 85749

Introduction:

We give an example of using an optical sensor as the probe on a CMM to align the mirrors of an optical system to each other, and to mechanical datums of the structure in which the mirrors are mounted. We use an optical system example because it better illustrates several advantages of optical probes in addition to demonstrating how a CMM can be used for product assembly and adjustment.

Among the points we want to make are that as mechanical tolerances of precision products become tighter, the finish must simultaneously become better to the point that the finish is in the realm of an optical or specular finish. Thus many mechanical parts now have a finish good enough for use with an optical sensor.

Further, many items of mechanical tooling are manufactured to optical quality both in finish and figure, or shape. Gauge blocks and angle gauge blocks are specular and flat to $0.1\text{ }\mu\text{m}$ or better. Plug gauges are cylindrical to the same accuracies and finishes. Chrome steel bearing and tooling balls are similarly well finished. Plug gauges, tooling and bearing balls are all commodity items costing at most \$30 each, a small fraction the cost of glass optics made to the same geometry.

The most important point of this paper is that by using an optical sensor as a probe on a CMM, one obtains real time visual feedback about an object's location in all three axes simultaneously - vastly increasing the utility of a CMM. The expanded utility of the CMM is not only for the assembly of opto-mechanics but also precision mechanisms not using optical components by making use of plug gauges and tooling balls. In addition to the value arising from expanding the functionality of the CMM there is a significant potential value in viewing a CMM as a tool for manufacturing, rather than only for quality assurance.

Example of an optical alignment problem:

Imagine a laser cavity module defined by two identical concave spherical mirrors, both of which need to be aligned to a baseplate that will, in turn, be located in another structure via a set of kinematic features. The laser beam exits the cavity on an axis (x-axis) defined by the centers of curvature of the two mirrors. We need to align the mirrors in position and angle relative to the kinematic locating features so that the laser beam is emitted from the desired location and in the desired direction. The basic hardware is shown in Fig. 1 where the kinematic locators are a cone, "V" groove and plane pad located in a baseplate.

The centers of the three balls define the xyz coordinate system of the baseplate. We require that the plane surfaces of the partially transmitting mirrors be normal to the laser beam (x-axis) and that the centers of curvature of the mirrors lie parallel to the x-axis a distance 0 in y and d in z above the x-axis (i.e. in the xz-plane).

Assume a fixture has been made with a two sided plane parallel mirror normal to the x-axis with 3 balls that fit in the locating features of the baseplate. This fixture, shown in Fig. 2, establishes the plane normal to the x-axis relative to the three balls for all subsequent assemblies.

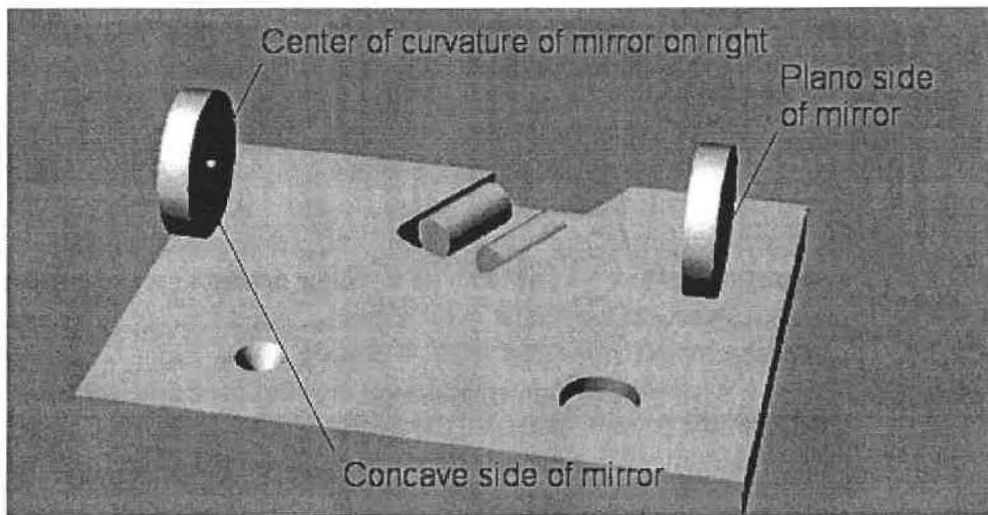


Fig. 1 Two plano concave mirrors ready for alignment relative to kinematic features of the baseplate

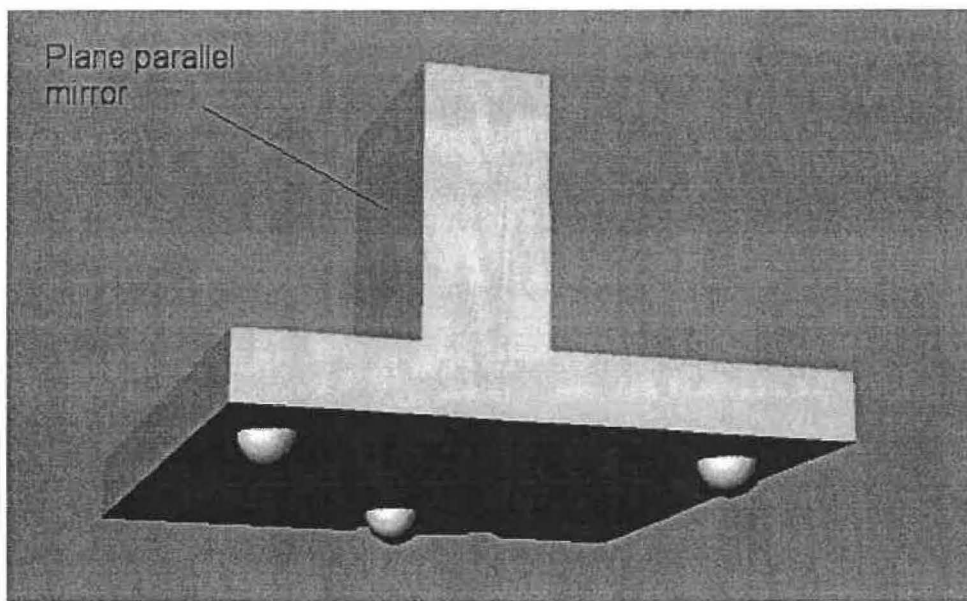


Fig. 2 Mirror fixture to establish axes of the coordinate system relative to the three balls

The optical sensor is shown schematically in Fig. 3. The sensor projects a focused point of light, captures its return on a CCD camera and displays the position and focus on a TV monitor. Optionally, the sensor can be fitted with a collimator to project a collimated beam, capture its return and display the angle offset of the reflected beam on the monitor. We demonstrate the sensor's use with schematics of the alignment process applied to the laser resonator.

Using a CMM for optical system assembly and alignment

Robert E. Parks and William P. Kuhn
Optical Perspectives Group, LLC
Tucson, AZ 85749

Introduction:

We give an example of using an optical sensor as the probe on a CMM to align the mirrors of an optical system to each other, and to mechanical datums of the structure in which the mirrors are mounted. We use an optical system example because it better illustrates several advantages of optical probes in addition to demonstrating how a CMM can be used for product assembly and adjustment.

Among the points we want to make are that as mechanical tolerances of precision products become tighter, the finish must simultaneously become better to the point that the finish is in the realm of an optical or specular finish. Thus many mechanical parts now have a finish good enough for use with an optical sensor.

Further, many items of mechanical tooling are manufactured to optical quality both in finish and figure, or shape. Gauge blocks and angle gauge blocks are specular and flat to $0.1\text{ }\mu\text{m}$ or better. Plug gauges are cylindrical to the same accuracies and finishes. Chrome steel bearing and tooling balls are similarly well finished. Plug gauges, tooling and bearing balls are all commodity items costing at most \$30 each, a small fraction the cost of glass optics made to the same geometry.

The most important point of this paper is that by using an optical sensor as a probe on a CMM, one obtains real time visual feedback about an object's location in all three axes simultaneously - vastly increasing the utility of a CMM. The expanded utility of the CMM is not only for the assembly of opto-mechanics but also precision mechanisms not using optical components by making use of plug gauges and tooling balls. In addition to the value arising from expanding the functionality of the CMM there is a significant potential value in viewing a CMM as a tool for manufacturing, rather than only for quality assurance.

Example of an optical alignment problem:

Imagine a laser cavity module defined by two identical concave spherical mirrors, both of which need to be aligned to a baseplate that will, in turn, be located in another structure via a set of kinematic features. The laser beam exits the cavity on an axis (x-axis) defined by the centers of curvature of the two mirrors. We need to align the mirrors in position and angle relative to the kinematic locating features so that the laser beam is emitted from the desired location and in the desired direction. The basic hardware is shown in Fig. 1 where the kinematic locators are a cone, "V" groove and plane pad located in a baseplate.

The centers of the three balls define the xyz coordinate system of the baseplate. We require that the plane surfaces of the partially transmitting mirrors be normal to the laser beam (x-axis) and that the centers of curvature of the mirrors lie parallel to the x-axis a distance 0 in y and d in z above the x-axis (i.e. in the xz-plane).

Assume a fixture has been made with a two sided plane parallel mirror normal to the x-axis with 3 balls that fit in the locating features of the baseplate. This fixture, shown in Fig. 2, establishes the plane normal to the x-axis relative to the three balls for all subsequent assemblies.

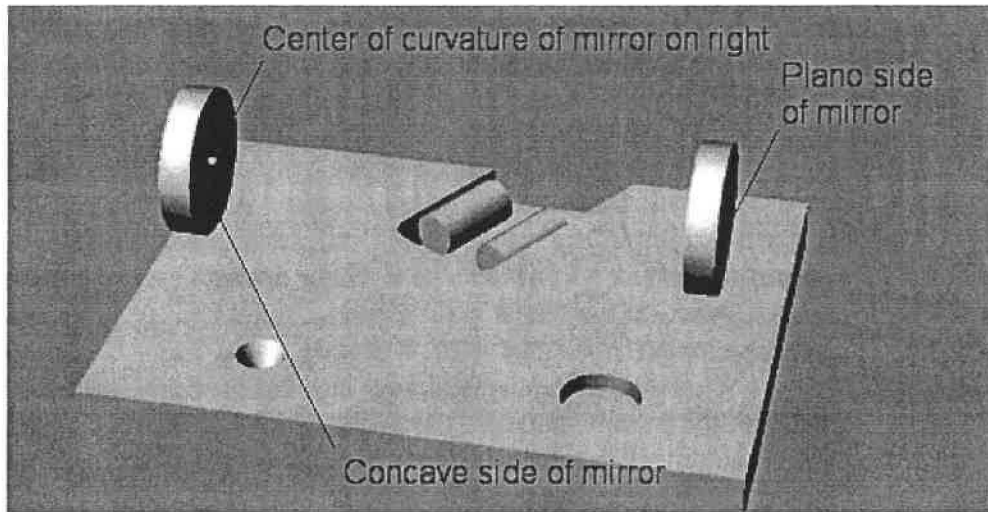


Fig. 1 Two plano concave mirrors ready for alignment relative to kinematic features of the baseplate

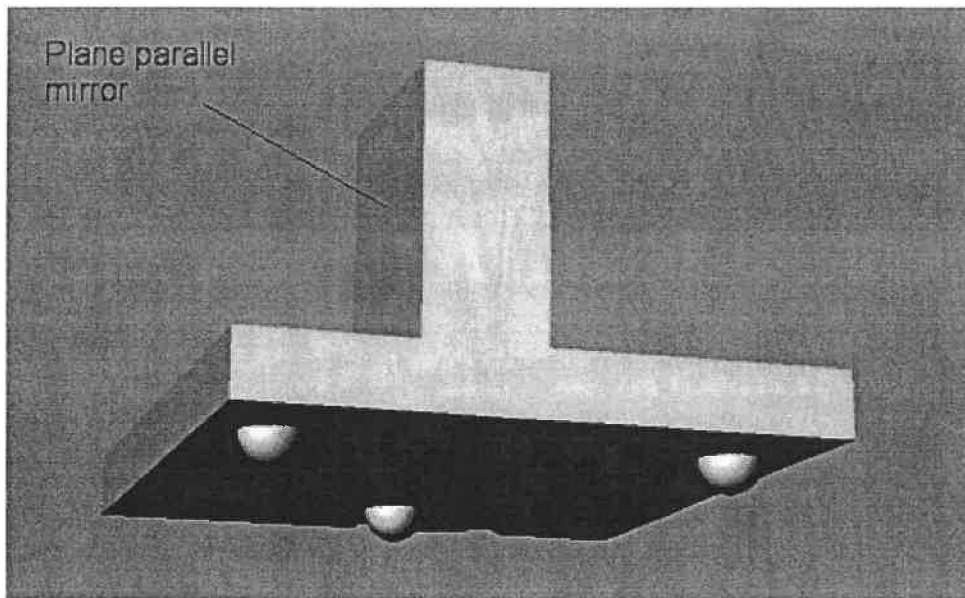


Fig. 2 Mirror fixture to establish axes of the coordinate system relative to the three balls

The optical sensor is shown schematically in Fig. 3. The sensor projects a focused point of light, captures its return on a CCD camera and displays the position and focus on a TV monitor. Optionally, the sensor can be fitted with a collimator to project a collimated beam, capture its return and display the angle offset of the reflected beam on the monitor. We demonstrate the sensor's use with schematics of the alignment process applied to the laser resonator.

1) With the sensor mounted on the CMM ram in place of the touch tip probe, move the probe until the projected spot is focused on a smooth surface. This produces a cat's eye reflection that cannot be decentered on the display even if the sensor axis is tilted relative to the smooth surface. The pixel location of the reflected spot on the display is the reference zero in x and y. The axial, or z, coordinate is zeroed when the return spot is as small in diameter as possible. The zeroes can be checked at any time in a series of measurements and the test is illustrated schematically in Fig. 4.

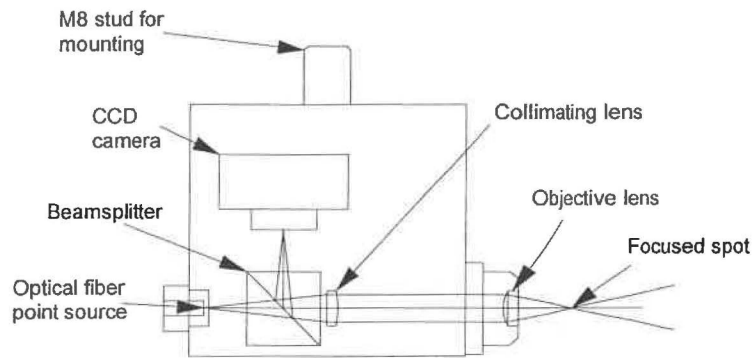


Fig. 3 PSM optical sensor used in place of a touch-tip probe shown approximately full size.

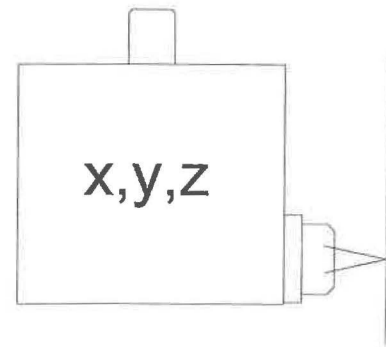


Fig. 4 Optical sensor getting a cat's eye reflection from a smooth surface to set the sensor zero in x, y and z.

2) The collimator attachment is added to the sensor and the fixture with the plane mirror is set on the laser resonator baseplate. The CMM probe adapter on the ram is adjusted in tip and tilt until the sensor axis defined by the collimator axis is normal to the plane mirror as shown in Fig. 5. This condition holds when the return light spot is centered on the sensor reference zero in x and y.

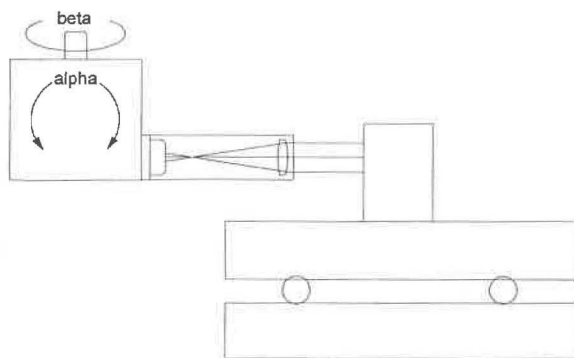


Fig. 5 The optical sensor is brought into angular alignment in two axes with the plane mirror on the fixture

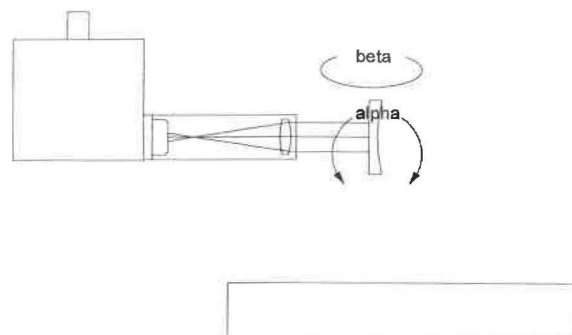


Fig. 6 The sensor is moved by the CMM to view the plano side of the mirror that is then adjusted in angle normal to the sensor.

3) The CMM is then used to move the sensor without changing its angular orientation to where the collimated beam strikes the plano side of the laser cavity mirror. The laser mirror is then adjusted in angle until the return light is made coincident with the reference position on the detector and video monitor. This adjustment can be made in real time by viewing the monitor as the mirror tip and tilt are adjusted as shown in Fig. 6. Angular adjustments are made without any use of CMM software.

4) The sensor is reversed so the collimator points to the left and steps 2 and 3 are repeated to align the plane side of the right hand laser mirror in angle.

5) The collimator attachment is removed and the sensor is rotated to point downward. The sensor is moved in x, y and z until the focus of the sensor is at the center of the master ball on the CMM table, that is, the reflected spot is centered at the reference location on the detector and is as small as possible. This location is the origin of the sensor in the CMM coordinate system. Note that all three coordinates are zeroed with one placement of the optical sensor and there is no offset for touch tip radius. The coordinates of the center of the ball are found directly with no mathematical fitting. All distances in the CMM coordinate system are measured relative to this location of the master ball as shown in Fig. 7.

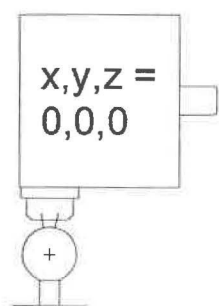


Fig. 7 Finding zero on CMM master ball

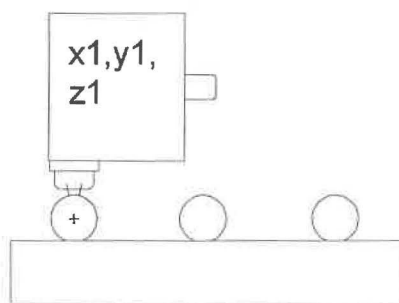


Fig. 8 Finding x, y, z coordinates of three balls on base

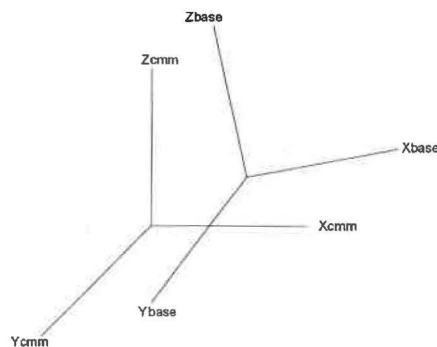


Fig. 9 Coordinate systems of CMM and baseplate

6) Next, the sensor is moved to the laser cavity baseplate and the locations of similar diameter balls in the three kinematic locations are measured in the same way as the master ball was located. The ball in the cone establishes three degrees of freedom. Since the "V" groove is aligned to the cone, the position of the ball in the groove is immaterial as is the case also with the ball on the plane pad. See Fig. 8. (A plug gauge the same diameter as the balls could also be used in the "V" groove.)

The measurement of the three balls on the baseplate is completed with just three settings of the sensor, one for each ball as was the case for the master ball. These three locations in x, y and z let the CMM calculate where the baseplate coordinate system is relative to the CMM coordinate system as shown in Fig. 9.

7) The sensor is now rotated 90 degrees so that it can be placed at the centers of curvature of the two cavity mirrors. The location of the mirrors along the x, or laser, axis is immaterial but the separation of the mirrors is such that the center of curvature of each should lie at the vertex of the other. To do this, the sensor is zeroed against the master ball because it has been rotated, Fig. 10.

8) The sensor is moved so that it gets a cat's eye reflection from the rear of the mirror on the left and is correctly located at $y = 0$ and $z = d$ in the baseplate coordinate system. The mirror on the right is moved in x, y and z until the light returning to its center of curvature is coincident with the zero ref-

erence of the sensor as shown in Fig. 11. (No adjustment is made in angle because the rear surface has already been adjusted normal to the laser beam.)

Fig. 11 shows the situation prior to the translational alignment of the mirrors. The left hand mirror is a little too high so there will be a small offset in the out going beam due to refraction and wedge in the mirror where the beam is passing through it. The right hand mirror is farther misaligned and must be moved upward in z to bring the reflected light back into the sensor.

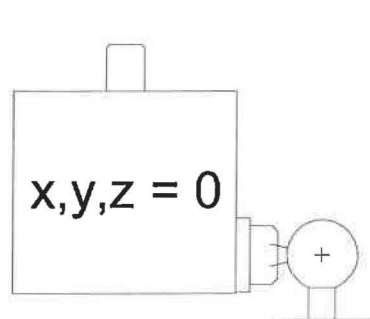


Fig. 10 Finding zero on the CMM master ball with the sensor rotated

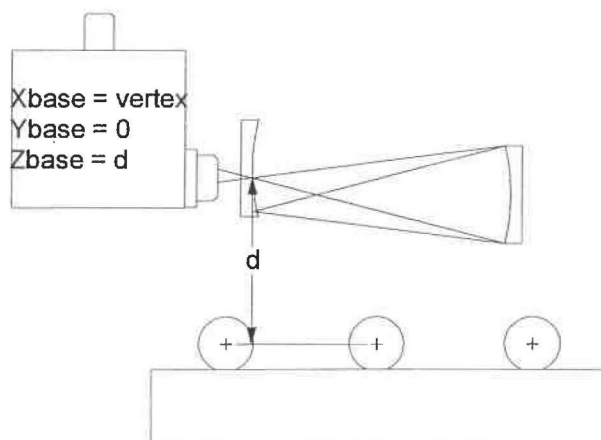


Fig. 11 The sensor properly located on the rear of the mirror surface and at the correct height.

9) Once the right hand mirror is adjusted vertically in z and horizontally in y so the return spot is centered on the detector reference, the sensor would be rotated 180 degrees, zeroed on the master ball and moved so that it was looking through the rear of the right hand mirror. Then the left hand mirror would be adjusted vertically and horizontally until the return were centered on the reference. The final alignment is shown in Fig. 12 as a superposition of the sensor looking at the centers of curvature of both mirrors. Since in this example the sensor must look through the mirror and this will add a small refractive error, the last steps should be repeated to correct any residual error in either mirror's position.

Conclusion:

Using an example we have shown how an optical sensor that projects a point source of light in conjunction with a CMM can be used to align specular spherical and plane surfaces in angle and position. The alignment can be done without any mathematically fitting of the surfaces or correction for touch tip ball radius. All the alignment is done without contacting the surfaces.

While the paper shows a schematic example of alignment, actual optical alignment has been done with a PSM optical sensor¹ to accuracies of $\pm 2 \mu\text{m}$ laterally and $\pm 4 \mu\text{m}$ axially in the location of ball centers of curvature. Plane surfaces can be aligned to the PSM sensor fitted with a collimator attachment to ± 4 seconds of arc. The ultimate accuracy in determining the distance between any two points using the visual method described would be the root-sum-square of the end point errors or about $\pm 2.8 \mu\text{m}$ plus the scale errors of the CMM.

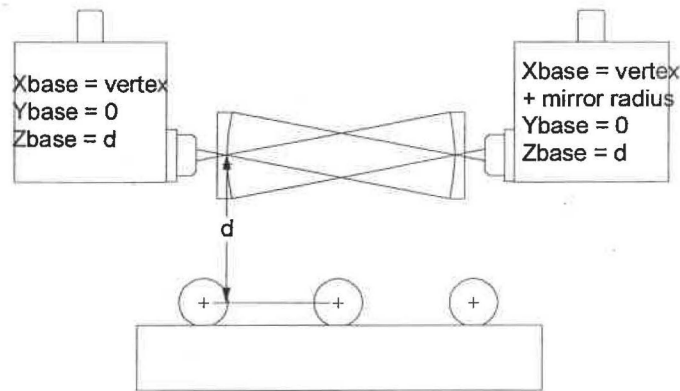


Fig. 12 The final steps of alignment of the laser cavity mirrors in translation where the optical sensor is looking both left and right. The mirror centers of curvature are a mirror radius apart as determined by the actual mirror radii in x , a distance d above the x axis in z and at $y = 0$.

The accuracy of the PSM itself can easily be improved at least an order of magnitude by using the PSM in an interferometric mode with the addition of some computational complexity. For many practical applications this improvement is unnecessary as the accuracy of CMM's is often no better over typical measurement distances.

CMM's used with touch tip probes are an excellent means for determining whether a mechanical feature is located where it should be. Once the feature is touched in several locations and its center, axis or plane determined by fitting, it is immediately clear if the feature is within tolerance limits. On the other hand, if the feature is not where it should be, it is a laborious process using a touch tip probe to correctly position the feature. As is clear from the example discussed here, the optical sensor can both determine a feature's location as well as direct its adjustment to the proper location because of immediate visual and electronic feedback in all three coordinates. It is this property of sensing a region of a feature in one probe setting, rather than a cluster of separate points, that makes the optical sensor so useful as an assembly and adjustment monitor.

This immediate position feedback allows one, manually or robotically, to adjust assemblies in real time. The ability to use a CMM in conjunction with an optical probe as an assembly tool vastly increases the value of the CMM in a manufacturing environment.

Finally, we used an optical example because it was easy to explain how an optical sensor could be used to align optics. Although most engineers do not think of tooling balls and plug gauges as optics, they are made to optical tolerances and can be used as optics in conjunction with an optical sensor. Thus the scheme described for optics will work just as well for purely mechanical assemblies.

¹ The PSM (patent pending) is available from Optical Perspectives Group, LLC, 9181 E. Ocotillo, Tucson, AZ 85749

Proposed new tests for evaluating CMM performance

Pereira, P. H. & Beutel, D. E.

Technical Services Division, Caterpillar Inc., Peoria, IL

Introduction

The current series of international standards for performance evaluation of Coordinate Measuring Machines (CMMs), ISO 10360, outline tests that allow manufacturers (OEMs) to publish specifications in such a way that it is more difficult for the non-expert CMM user to compare different brands of machines. The intent is to improve competitive advantage by having a very attractive, yet many times non-representative, value denoting the machine possible accuracy. Typically these values can only be achieved under very strict conditions. Once values are established and published in accordance with current standards, it is very difficult to challenge them without executing (expensive) tests.

The current test procedure is open enough that, for example, a CMM manufacturer can use artifacts made of very low coefficient of thermal expansion (CTE) materials to carry out their tests without the need for tight environmental control obtaining better results to be published on their literature. However, users do not, for the most part, measure parts made of low CTE materials and cannot afford tight temperature control. Recently, a manufacturer started advertising a new precision CMM with specifications according to ISO 10360-2. Their specification for MPE_E is around $1.5 \mu\text{m}$ for a 1 m length with a claimed temperature range of $\pm 2^\circ\text{C}$. However, just the uncertainty of the test considering the effect of temperature on a normal CTE (steel) artifact is almost as large as the specification. Such specification is possible, i.e. it is compliant, because, according to the current version of the Standard [1], the manufacturer is not required to disclose the actual test conditions and is free to use any material for the artifacts.

Modified tests are necessary to level the playing field while at the same time, keeping the overall task of performance evaluation to a low, manageable cost. The overall objective is to have the specifications convey a realistic picture of the machine behavior when measuring real parts. One possibility for such tests is explained and results are shown comparing existing and proposed procedures.

Proposed tests and results

In order to minimize the possibilities of misinterpretation of performance values for machines, two main modifications are proposed. First, that a specification for a normal (close to that of steel) CTE artifact should be provided by the manufacturer, with additional specifications for a low CTE artifact being optional. Since the current version of the Standard states the manufacturer is to choose the probe stylus, obviously the most used one is a short straight down configuration because it is more rigid and the results are generally better. This is the reason for the second proposed modification where an offset probe should be required for the volumetric tests.

By adding two plane diagonals with five length measurements each repeated three times to the existing seven positions [1], and requiring them to be measured with an offset probe, it is possible to realize the mentioned benefits.

A supplementary useful parameter that could be extracted from the same data is a repeatability value. Calculated from the range of results from the repeated measurements, this repeatability parameter provides more information about the machine without additional testing.

Figure 1 shows the result on a MMZ 20 30 16 machine with a Vast scanning probe head evaluated as per the current Standard [1]. The artifact was a 1 m steel step gage. Seven positions were used, including three parallel to each of the axes and four body diagonals. The plot shows only the worst of three repetitions for each of five lengths on the step gage. A total of 105 measurements were taken. The largest error is 6.4 μm .

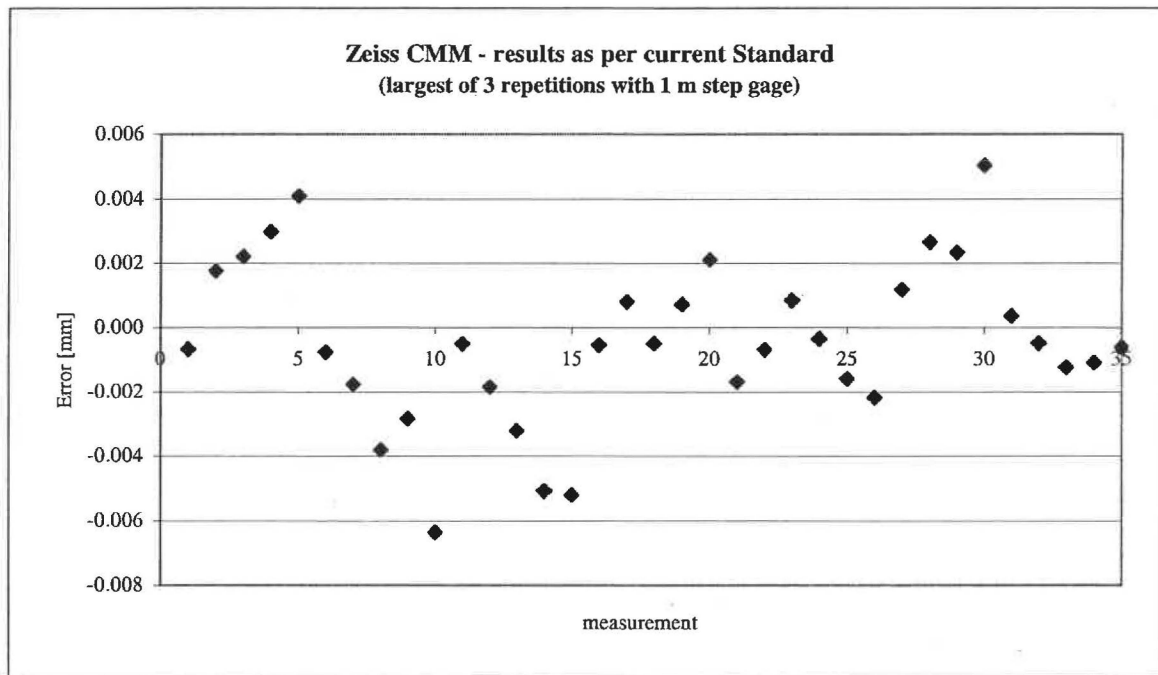


Figure 1 – MMZ results with probe straight down

Figure 2 has the results from the same MMZ machine tested using a laser ball step gage (LBSG) [3] with a 200 mm offset probe. Five lengths were measured three times each on two plane diagonals for a total of 30 measurements all shown on the plot. With the LBSG, longer lengths were used covering a larger volume of the machine. The worst-case error for this test was 18.8 μm thus three times that of the current Standard. Maximum repeatability, or worst case variation, was 0.8 μm .

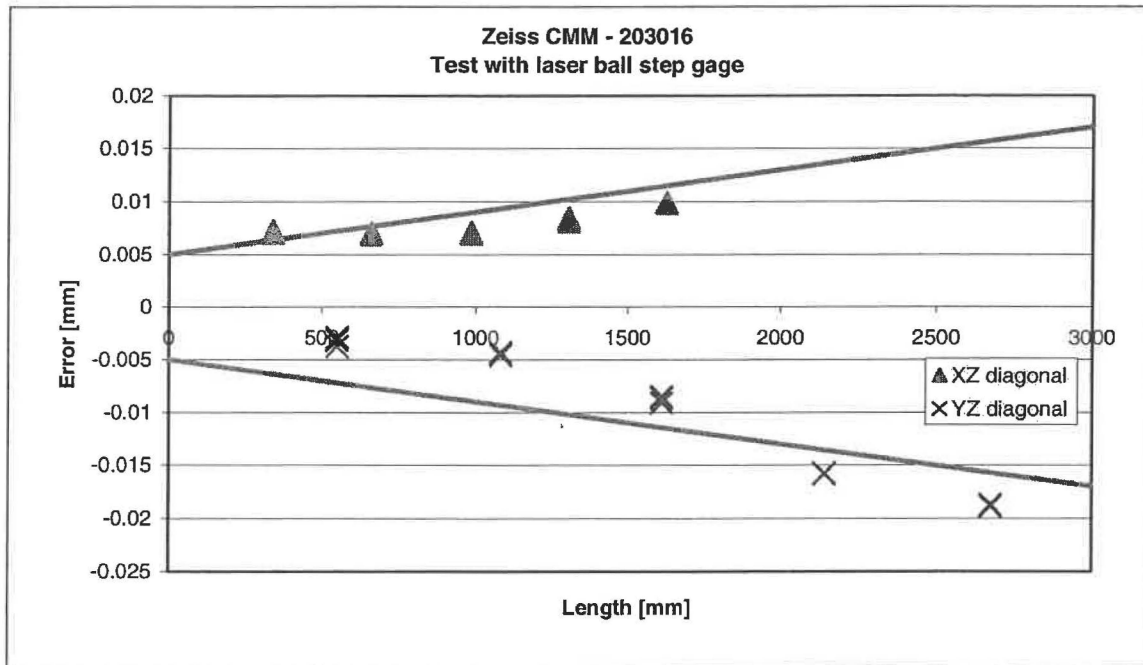


Figure 2 – MMZ results with offset probe

Figure 3 is a photo of the test setup for the proposed tests on the MMZ subject machine. To actually use the LBSG artifact, which is very practical for larger machines to achieve the required coverage of 66% of the body diagonal, another minor addition is needed to the Standard. In its current form, only artifacts with parallel faces, like a mechanical step gage, are allowed for this test. The averaging effect when measuring a sphere must be properly accounted for to allow different artifacts, used with the same procedure, to output comparable results.

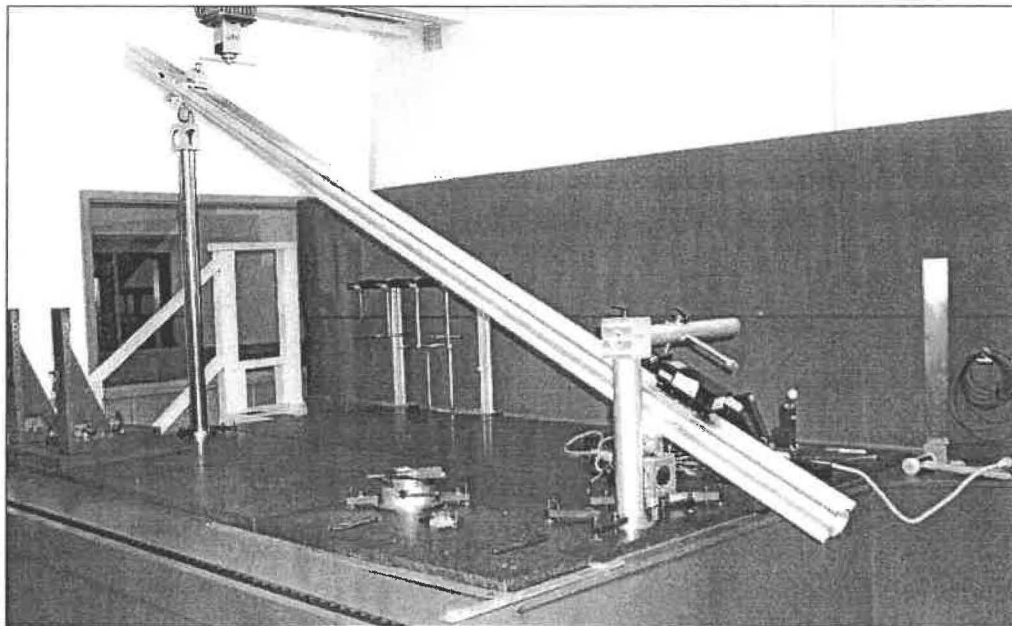


Figure 3 – Test setup on MMZ 20 30 16 – YZ diagonal

A 1 m steel step gage was used to evaluate a Cygnus 20 12 10 machine equipped with a PMM scanning probe head according to existing Standard [1]. Seven positions including three aligned with the machine axes and four body diagonals were used. Five lengths were measured three times. Figure 4 displays the results of this evaluation. The largest error comes to 2.9 μm .

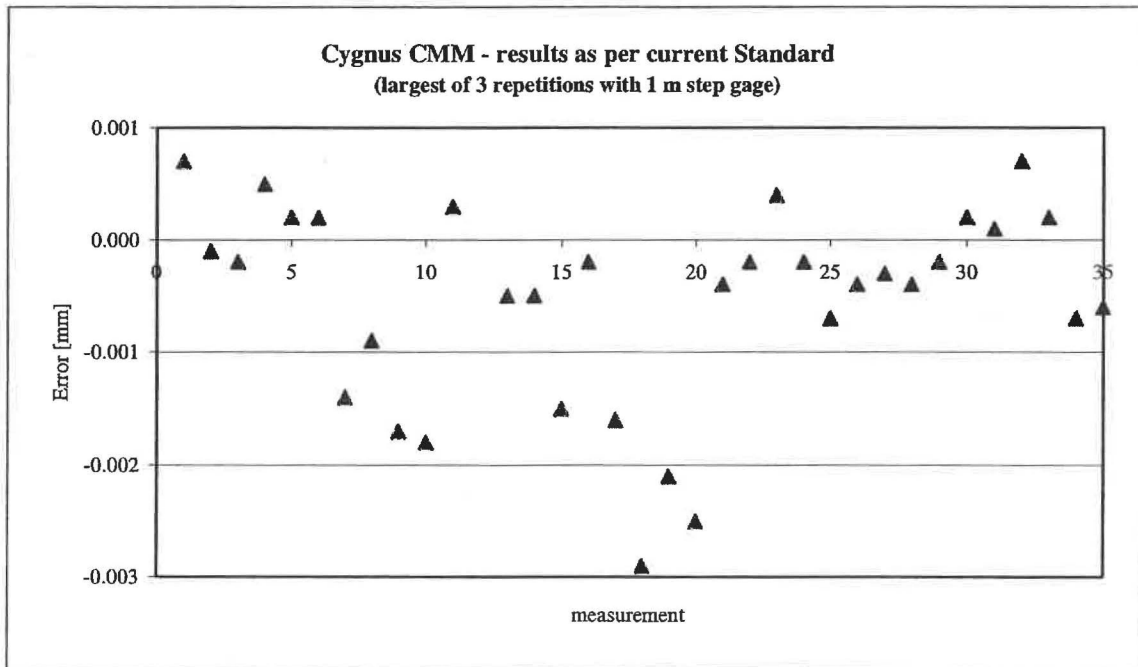


Figure 4 – Cygnus results with probe straight down

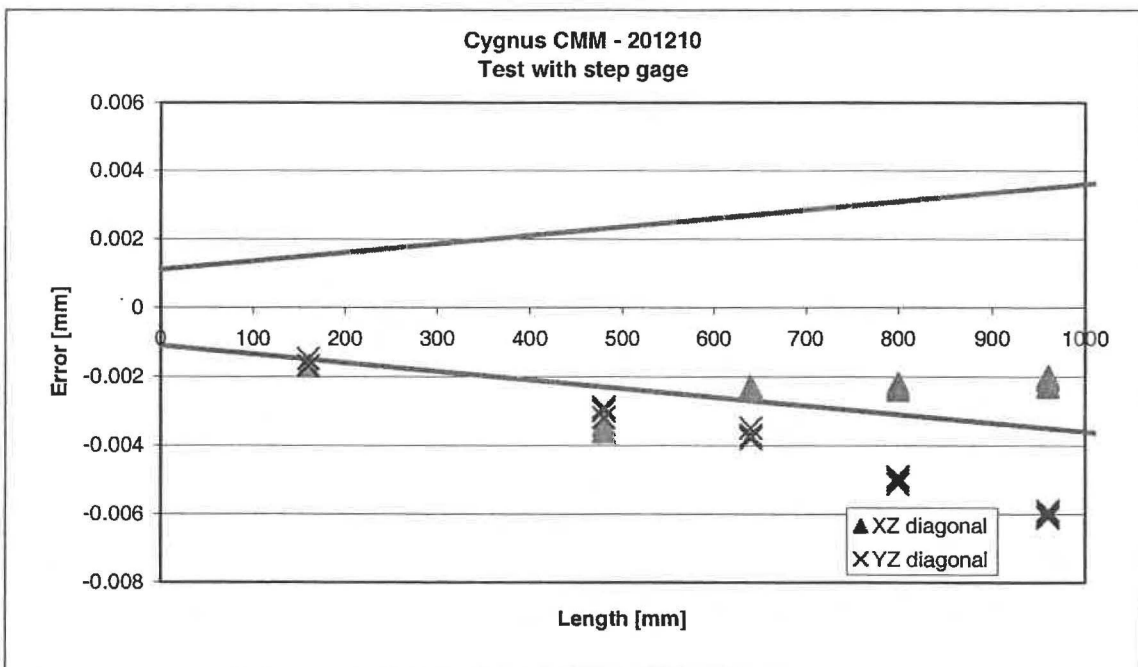


Figure 5 – Cygnus results with offset probe

Figure 5 shows the results of the same Cygnus machine evaluated with a 200 mm offset probe on two plane diagonals. Again five lengths of a step gage were measured three times each on both positions. The plot has all 30 measurements. Maximum non-repeatability, or worst-case variation, was 0.3 μm . The maximum error was 6.1 μm or twice that of the evaluation according to current Standard.

Discussion

Table 1 below displays the summary of the test results for comparison. There is clearly a difference where the existing tests show better values. For both machines, the offset probe certainly uncovers more geometric errors. For the MMZ machine, with the LBSG, a considerably larger volume of the machine was evaluated perhaps causing the more substantial increase in the error. The repeatability values are useful to demonstrate how repeatable the machine can be without an extra test.

Table 1 – Summary of results

Machine	E as per current Standard	Proposed	
		Repeatability	Volumetric error (E)
MMZ	6.4 μm	0.8 μm	18.8 μm
Cygnus	2.9 μm	0.3 μm	6.1 μm

Conclusions

As normal, change comes with certain resistance. Users and particularly vendors may state that they are comfortable to read results as per the current Standard and that all setups (fixtures, artifacts, programs, etc) are in place to test machines as such. However, it is also very important that the evaluation tests represent real life applications. From the results shown:

- The current tests minimize the errors making the machine better than it really is
- Thermal effects are not taken into account
- Parallel face artifacts are not adequate for larger machines
- Requiring uncertainty statements to be shown [5] for performance evaluation tests have not significantly changed anything yet

It is argued the modified tests will generate values more closely related to actual part measurements that will be more useful to all involved.

References

1. ISO 10360:2-2001, Geometrical product specifications (GPS) – Acceptance and reverification test for coordinate measuring machines (CMM) – Part 2: CMMs used for measuring size
2. ISO 10360:5-2000, Geometrical product specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM) – Part 5: CMMs using multiple-stylus probing systems
3. Phillips, S.D.; Sawyer, D.; Borchardt, B.R.; Ward, D.; Beutel, D.E., "A novel artifact for testing large coordinate measuring machines", Precision Engineering, Vol. 25, n. 1, Jan/2001
4. ASME B89.4.1-1997, "Methods for performance evaluation of coordinate measuring machines", The American Society of Mechanical Engineers.
5. ISO 14253 series, Geometrical product specifications (GPS) – Inspection by measurement workpieces and measuring equipment

Keywords: CMM, standards, performance tests, CTE uncertainty

NEW CONCEPT GEOSTEP

Eugene Gleason
Ball Tech, Los Angeles, California

The Geostep is a new concept in Coordinate Measuring Machine calibration. It uses several fundamental concepts of physics to achieve the ultimate in calibration accuracy. It uses multiple spherical artifacts that are of almost perfect geometry and of exactly the same diameter. These spheres are made of high chrome, high carbon stainless steel that is hardened to 58 HRC and thermal cycled for long-term dimensional stability.

The spherical geometry by definition has one point in three-dimensional space that defines its perfect position. The variety of vector forces generated when measuring a sphere applies forces to the test probe from all directions so it truly evaluates the probes performance in all circumstances. Probing a nearly perfect sphere tests the entire machines ability to measure and document its perfect position in the x - y and z coordinates.

By probing two spheres that are rigidly mounted a well-known distance apart, the three scales are added to the calibration equation. By carrying this concept further and adding a whole series of balls on the same centerline, additional basic principles of physics apply themselves. As the artifact gets longer, more of the C. M. M.'s error sources begin to show up. Systematic scale errors are made manifest because the line of balls are intentional spaced varying distances apart. All of the fundamentals of ball bar technology apply to the Geostep.

The simple act of measuring the Geostep in a series of well-chosen positions will check all 18 of the possible geometry errors of a Coordinate Measuring Machine. This is based on the fact that the dimensions of the Geostep are fixed so that any variations from position to position are errors in the measuring machine. The longer geometry lends itself to reversal technology, which enhances the accuracy and can even detect original calibration errors. First the Geostep is placed in a compound attitude, such as an inclined position across a body diagonal and then it is reversed 180 degrees. This simple test accurately evaluates a whole series of potential scale errors and shows up squareness and straightness errors if they exist. When the same test is performed on the other body diagonal you have a very quick, interim or Monday morning evaluation of the entire machine.

This is an archival test artifact that requires an occasional traceable calibration.

The line of balls is placed on the neutral bending plane of the extremely rigid beam construction. This reduces small bending moments to second order cosign errors that are of insignificant magnitude.

During the eight years of development many features of this device were perfected. The large 3-inch diameter window around the ball provides more than enough pre-travel for accurate, repeatable measurements of each ball's position, by any make of C.M.M.

Unlike the ball mounting techniques used on other artifacts the balls of the Geostep retain their almost perfect sphericity and original size.

To prevent elastic deflection of the balls true position, by the probing force, during measurements, a deep hole is drilled into the ball and into the post that supports the ball. A solid Tungsten Carbide shaft is used to mount the ball to the body of the Geostep. This gives the ball the same rigidity as the body of the beam itself. Remember that tungsten carbide has a stiffness or young's modules of 98,000,000 psi, which is more than four times that of cast iron.

Although virtual CMM evaluation shows that this device does evaluate straightness of the machine axii, the edges of one side rail can be flat lapped to provide a straight reference datum. This arrangement lends itself to reversal verification of the artifacts straightness.

The body of the Geostep is produced to near net shape by the "stable cast" process, from a special alloy iron to assure long-term dimensional stability. The entire body of the artifact is sealed with a hard metal coat that is very corrosive resistant.

The thermal coefficient of expansion for the materials that are used to construct the Geostep is 6.4 microinches per inch per degree Fahrenheit, at temperatures near the 68-degree standard. This expansion rate is the same as most steel parts.

The device is rigidly supported by a precision honed 2-inch diameter hole (50 mm) in the very center of the part. This well-balanced arrangement divides the bending moments in half so any deflections caused by the probing forces are minute. The position of the Geostep is rigidly fixed by clamping two annular flat parallel rings surrounding the two-inch diameter hole. This isolates the clamping force, to prevent distortion of the Geostep.

The standard support mechanism allows a full 360-degree of rotation and 120 degrees of articulation. This basically depicts a large spherical shell from each location of the rigid support mechanism on the C.M.M. table.

There is also a NIST developed version of the support stand that is somewhat more sophisticated. It will index the Geostep to pre-selected positions in both planes and can be relocated in the same place on the machine table time after time. Learning procedures can be used so that re-measurements of the artifact can be made automatically.

For a through machine evaluation very low horizontal measurements must be made. For this application a rugged kinematically coupled base plate is available.

The Geostep is the culmination of eight years of research. It is a simple, single, element calibration device that will give a total calibration of all 21 rigid body errors as well as the meridian of the flexible or elastic errors. The only limitation to the perfection of the Coordinate Measuring Machine evaluation and calibration by the Geostep is the accuracy of the original calibration of the artifact.

This device has been commercially available for three years and is well on its way of becoming the world standard for C.M.M. calibration.

NIST is providing a calibration service for this artifact that is accurate to less than one part per million. The full size artifact is 34 inches (860 mm) long with 10 ultra precise spheres placed on a common centerline in an uneven pattern that avoids synchronistic errors.

Two shorter versions of the Geostep are available for calibration of smaller machines. A 26 5/8-inch (676 mm) version with 8 spheres and a 16 5/8-inch (424 mm) version with 6 spheres. All three versions use identical construction. They are one and one half inch thick and four inches wide.

A big factor in the function of the Geostep is the things that the Geostep doesn't depend on. There is no laser with its dependency on dust point, or barometric pressure and it requires no power, and it does not generate any heat.

The device weighs less than 20 pounds so that a single technician can perform the entire machine calibration.

The device is extremely rugged so it can be safely transported in a simple container.

This Geostep costs only a small fraction of any other complete calibration system. It has all of their advantages and none of their limitations.

A 60-inch version and an 8-inch version of the device are in development.

In addition to the routine calibration procedures this single device is long enough to check thermal drift effect and to perform repeatability tests.

Six Degree of Freedom Precision Measurement System

Hongliang Cui, Zengxi Pan, and Zhenqi Zhu
Department of Mechanical Engineering
Stevens Institute of Technology
Hoboken, NJ 07030

Abstract

Assessing the performance of industrial robots and machine tools has been a time consuming task and involves expensive metrology devices with 6 degrees of freedom. To reduce the cost and time, a device is being developed and this paper introduces the device and the mathematical models. The device based on the principles of Stewart platform, measures both the translational errors and angular errors with six linear encoders. This measurement system including hardware and software, has the features of compact, easy to setup, easy to use, limited testing time, and low cost. The measurement is independent of setup accuracy. The device will be useful for evaluating machine tool performance, evaluating the performances of industrial robots, evaluating the motion errors of other machine systems, calibrating machine tools and industrial robots, and calibrating any other multi-axis motion systems as a six degree of freedom ruler.

Keywords: robot accuracy, performance evaluation, six degree of freedom, pose measurement, robot calibration.

1. Introduction

New robotic applications such as grinding and machining have made evaluating the performance of industrial robots more and more important. These new developments also revive the interest in robotic performance evaluation. Given the mechanical configurations of industrial robots and the popular six degrees of freedom, industrial robots have to be evaluated with metrology device or system of 3 or more degrees of freedom. Evaluation methods and equipment are needed to measure the spatial pose of robot efficiently with low cost.

Several methods are available for characterizing robot performance in accordance with ISO 9283 "Manipulating Industrial Robots Performance Criteria and Related Test Methods". Eight major performance measuring methods and techniques are introduced in the technical report ISO TR 13309 including the accurate, easy-to-use but costly laser tracking technique. The pros and cons of existing multi-degrees of freedom measuring systems, including laser tracker, straight edges, multi-probes at certain check points, image and scanning techniques etc, are well documented [Lau and Hocken, 1984; Van Brussel, 1990;

Jiang et al, 1988]. Pose measurement of robotic end effector has been the focus [Ziegert and Datsis, 1990; Zhu and Cui, 2001, 2003].

2. Mathematic Model for the Six Degree of Freedom Measurement System

Over the past two decades, six-degree-of-freedom parallel manipulators have received a great deal of attention because their attractive characteristics such as high rigidity, high local dexterity, low inertia effect and compact size. There exist various configurations of the Stewart platforms and variation of the platforms and connecting joints. Figure 1 shows a prototype 6 DOF measuring device. It was design to ease setup and reduce measurement time. It's setup, calibration, and measurement are based on the mathematic models described below.

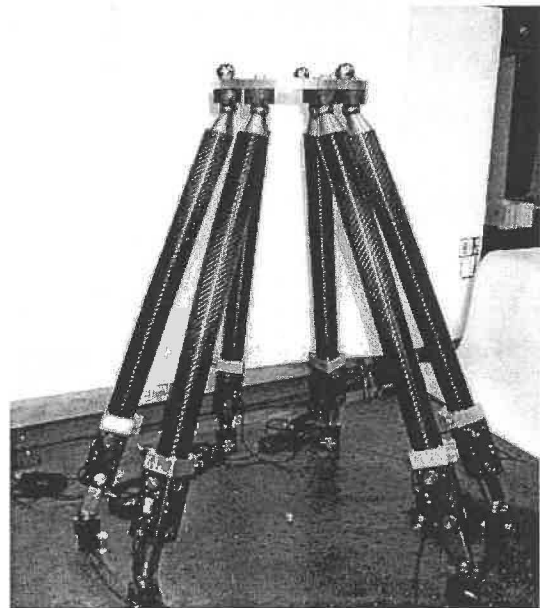


Figure 1 6-DOF Measuring Device [Zhu and Cui, 2001, patent pending]

$$-\begin{bmatrix} \frac{\partial f_1}{\partial g_1} & \frac{\partial f_1}{\partial g_2} & \dots & \frac{\partial f_1}{\partial g_N} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_6}{\partial g_1} & \frac{\partial f_6}{\partial g_2} & \dots & \frac{\partial f_6}{\partial g_N} \end{bmatrix}_{6 \times N} \cdot \begin{bmatrix} dg_1 \\ dg_2 \\ \vdots \\ dg_N \end{bmatrix}_{N \times 1} \quad (5)$$

From Eq. (5) above, we have

$$dG = J_2 dg \quad (6)$$

Substitute Eq.(6) into Eq.(4) to obtain

$$J_1 dX = J_2 dg$$

Finally $dX = (J_1^{-1} J_2) dg$

The Jacobian matrix is obtained as $J_1^{-1} \cdot J_2$

$$J = J_1^{-1} \cdot J_2 = \begin{bmatrix} \frac{\partial f_1}{\partial x} & \frac{\partial f_1}{\partial y} & \frac{\partial f_1}{\partial z} & \frac{\partial f_1}{\partial \alpha} & \frac{\partial f_1}{\partial \beta} & \frac{\partial f_1}{\partial \gamma} \\ \frac{\partial f_2}{\partial x} & \frac{\partial f_2}{\partial y} & \frac{\partial f_2}{\partial z} & \frac{\partial f_2}{\partial \alpha} & \frac{\partial f_2}{\partial \beta} & \frac{\partial f_2}{\partial \gamma} \\ \frac{\partial f_3}{\partial x} & \frac{\partial f_3}{\partial y} & \frac{\partial f_3}{\partial z} & \frac{\partial f_3}{\partial \alpha} & \frac{\partial f_3}{\partial \beta} & \frac{\partial f_3}{\partial \gamma} \\ \frac{\partial f_4}{\partial x} & \frac{\partial f_4}{\partial y} & \frac{\partial f_4}{\partial z} & \frac{\partial f_4}{\partial \alpha} & \frac{\partial f_4}{\partial \beta} & \frac{\partial f_4}{\partial \gamma} \\ \frac{\partial f_5}{\partial x} & \frac{\partial f_5}{\partial y} & \frac{\partial f_5}{\partial z} & \frac{\partial f_5}{\partial \alpha} & \frac{\partial f_5}{\partial \beta} & \frac{\partial f_5}{\partial \gamma} \\ \frac{\partial f_6}{\partial x} & \frac{\partial f_6}{\partial y} & \frac{\partial f_6}{\partial z} & \frac{\partial f_6}{\partial \alpha} & \frac{\partial f_6}{\partial \beta} & \frac{\partial f_6}{\partial \gamma} \end{bmatrix}^{-1} \cdot \begin{bmatrix} \frac{\partial f_1}{\partial g_1} & \frac{\partial f_1}{\partial g_2} & \dots & \frac{\partial f_1}{\partial g_N} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_6}{\partial g_1} & \frac{\partial f_6}{\partial g_2} & \dots & \frac{\partial f_6}{\partial g_N} \end{bmatrix}$$

2.2 Newton-Raphson Numerical Method

Because of the number of parameters involved as well as the number of error sources involved, the kinematic problem becomes very complicated. No analytical solution can be obtained but numerical solution. The 6-dof precision measurement system, as a general case of parallel robots, its forward kinematic problem is, therefore, very complicated. The Newton-Raphson method as an effective numerical method can be applied to calculate the forward problem, with an accurate Jacobian matrix obtained.

Newton-Raphson method is represented by

$$X_{n+1} = X_n - [F'(X_n)]^{-1} \cdot F(X_n) \quad (7)$$

With the six chain equations obtained before, the following can be obtained

$$[F'(X_n)]^{-1} = INV \begin{bmatrix} \frac{\partial f_1}{\partial x} & \frac{\partial f_1}{\partial y} & \frac{\partial f_1}{\partial z} & \frac{\partial f_1}{\partial \alpha} & \frac{\partial f_1}{\partial \beta} & \frac{\partial f_1}{\partial \gamma} \\ \frac{\partial f_2}{\partial x} & \frac{\partial f_2}{\partial y} & \frac{\partial f_2}{\partial z} & \frac{\partial f_2}{\partial \alpha} & \frac{\partial f_2}{\partial \beta} & \frac{\partial f_2}{\partial \gamma} \\ \frac{\partial f_3}{\partial x} & \frac{\partial f_3}{\partial y} & \frac{\partial f_3}{\partial z} & \frac{\partial f_3}{\partial \alpha} & \frac{\partial f_3}{\partial \beta} & \frac{\partial f_3}{\partial \gamma} \\ \frac{\partial f_4}{\partial x} & \frac{\partial f_4}{\partial y} & \frac{\partial f_4}{\partial z} & \frac{\partial f_4}{\partial \alpha} & \frac{\partial f_4}{\partial \beta} & \frac{\partial f_4}{\partial \gamma} \\ \frac{\partial f_5}{\partial x} & \frac{\partial f_5}{\partial y} & \frac{\partial f_5}{\partial z} & \frac{\partial f_5}{\partial \alpha} & \frac{\partial f_5}{\partial \beta} & \frac{\partial f_5}{\partial \gamma} \\ \frac{\partial f_6}{\partial x} & \frac{\partial f_6}{\partial y} & \frac{\partial f_6}{\partial z} & \frac{\partial f_6}{\partial \alpha} & \frac{\partial f_6}{\partial \beta} & \frac{\partial f_6}{\partial \gamma} \end{bmatrix}$$

This equation is applied to calculate the forward kinematic problem existed in the process of calibrating the system and carrying out error analysis.

The 6-dof measuring system [Zhu and Cui, 2001] consists of the device shown in Figure 1, data acquisition, and application software. Optical linear encoders (from Heidenhain) of submicron resolution are used in measuring the linear displacements. The top platform is connected to any object with its motion to be measured, usually a tool holder or robotic end-effector. The device can be set up quickly and its configuration can be updated in the setup process.

3. Error Budget

When the SVD decomposition is completed and a linearly independent set of error model parameters determined, the Error Budget can be determined. The mathematical description of the error budget is as follows:

$$\begin{aligned} J &= U \cdot S \cdot V^T \\ dX &= J \cdot dg = U \cdot S \cdot V^T \cdot dg \\ U^T \cdot dX &= S \cdot V^T \cdot dg \end{aligned}$$

Assume $U^T \cdot dX = d\bar{X}$ and $V^T \cdot dg = d\bar{g}$. So we have $d\bar{g} = d\bar{X}/S_{ii}$, finally,

$$dg = (V \cdot U^T \cdot dX)/S_{ii}$$

Thus if the dX is given as the accuracy of the system, the error budget dg can be determined. The six chain equations are created for the six link lengths, as follows:

$$F = \begin{bmatrix} f1(link1_points, TCP_points) \\ f2(link2_points, TCP_points) \\ f3(link3_points, TCP_points) \\ f4(link4_points, TCP_points) \\ f5(link5_points, TCP_points) \\ f6(link6_points, TCP_points) \end{bmatrix}$$

Where $TCP_point = f(px, py, pz, \alpha, \beta, \gamma)$
and ϵ is a collection of all the design parameters. Thus,

$$F = \begin{bmatrix} F1(\epsilon, px, py, pz, \alpha, \beta, \gamma) \\ F2(\epsilon, px, py, pz, \alpha, \beta, \gamma) \\ F3(\epsilon, px, py, pz, \alpha, \beta, \gamma) \\ F4(\epsilon, px, py, pz, \alpha, \beta, \gamma) \\ F5(\epsilon, px, py, pz, \alpha, \beta, \gamma) \\ F6(\epsilon, px, py, pz, \alpha, \beta, \gamma) \end{bmatrix}$$

An error model is developed based on the system of equations as described above. All parameters are defined to represent the entire system. All parameters include all the D-H parameters for the links, as well as the coordinates (x, y, z) of the 6 points at both edges of the 6 links, respectively.

4. Conclusion

A 6-dof precision measuring system is introduced. The mathematical models are developed for setting up, calibrating, and error analysis of the system. Newton-Raphson numerical method is used and the Jacobian matrix is also derived. The method can be used in calibrating the device and compensating various types of errors including thermal, dimension and setup errors. The system features low cost, easy and quick setup, and relative large work volume.

References

1. Cui, H. and Z. Zhu, 2002, "Errors and Corrections of Robotics Standard ANSI/RIA/R15.05-1-1990," ETC 2002/MECH-34368.
2. International Organization of Standardization (ISO), , 1995, "Manipulating Industrial Robots Informative Guide on Test Equipment and Metrology Methods of Operation for Robot Performance Evaluation in Accordance with ISO 9283", ISO TR 13309.
3. International Organization of Standardization (ISO), 1990 "Manipulating Industrial Robots - Performance Criteria and Related Test Methods," ISO 9283.

4. Jiang, B. C., , J.T. Black, R. Duraisamy, 1988, "A Review of Recent Developments in Robot Metrology," Journal of Manufacturing Systems, Vol. 7, n4, pp.339-356.
5. Johann P. Prenninger, Karl M. Filz, Markus Vincze, Helmut Gander, 1995, "Real Time Contactless Measurement of Robot Pose in Six Degrees of Freedom", Measurement, Vol. 14, pp. 255-264
6. Lau, K. and R.J. Hocken, 1984, "A Survey of Current Robot Metrology Methods," Annals of the CIRP Vol. 33/2, pp.485-488.
7. Van Brussel, H., 1990, "Evaluation and Testing of Robots," Annals of the CIRP Vol. 39/2, pp.657-664.
8. Zhu, Z. and H. Cui, 2003, "Conflict Definitions and Mistakes in American Industrial Robotics Standard for Static Performance Evaluation," International Journal of Industrial Robots (in press).
9. Zhu, Z. and H. Cui, 2001, "6 DOF Measurement System," June, 2001. (patent pending).
10. Ziegert, J. and P. Datseries, 1990, "Robotics Calibration Using Local Pose Measurements," Vol. 5, n2, pp. 68-76.

Evaluation of CMM Tolerance Calculation Software

Paul D. Thomas

Mitutoyo America Corporation, City of Industry, CA

Abstract

Coordinate measuring machine (CMM) software has long used least-squares fit calculations to construct resolved geometry representations of measured features. The National Institute of Standards and Technology (NIST) and other national testing bodies have been evaluating the performance of least-squares algorithms for many years, long before the ASME B89.4.10-2000 and the ISO 10360-6:2001 standards for evaluating CMM software were available. Least-squares analysis is a very useful tool when dealing with measurement uncertainty or the statistical control of a manufacturing process. The problem, however, is that the ASME Y14.5M-1994 and the ISO 1101 standards on dimensioning and tolerancing never specify the use of a least-squares fit.

Tolerances of form such as straightness of a line, flatness of a plane, circularity of a circle, and cylindricity of a cylinder require a Chebyshev (minimum zone) fit. A feature of size such as a circle, cylinder, sphere, or parallel plane requires a mating envelope (maximum inscribed or minimum circumscribed) fit for tolerances of location and orientation and when used as a datum feature. If CMM software gives inaccurate results for non-least-squares resolved geometry calculations, then the tolerance calculation based on the resolved geometry is also inaccurate.

A formal evaluation of the performance of non-least-squares fits is not currently available from the national testing bodies. This problem is especially critical because the well-tested algorithms used to solve least-squares fits, such as the Levenberg-Marquardt method, cannot be used on non-least-squares fits because the derivatives of the objective functions are no longer continuous. General multivariable minimization algorithms such as the downhill Simplex method sometimes give poor results for non-least-squares fits on seemingly simple data sets. Non-least-squares fits are especially difficult because there may be more than one stable solution – the global solution can only be determined after finding all possible solutions.

CMM software is tested using reference data sets that have a known solution for a specified non-least-squares fit. This paper examines the basic geometry that controls the stability of each non-least-squares fit. Once these simple geometric rules are understood, reference data sets are easy to construct.

1 Introduction

The purpose of this paper is to show how easy it is to generate reference data sets for lines, planes, circles, and spheres using simple geometric rules, that give known solutions to non-least-squares fits. By generating the reference data sets in a standard format, such as the Dimensional Measuring Interface Standard (DMIS 4.0), the CMM software can be immediately tested and evaluated by running an offline simulation. If the CMM software results don't agree with the known solution, it is a simple calculation to verify which solution is best and whether the reference data set generator or the CMM software is flawed. If desired, the reference data set can be verified using a brute force calculation that tries all possible combinations of the minimum number of points of contact.

By understanding the stability criteria of each non-least-squares fit, the minimum number of points of contact can be established for a given feature with a known size, orientation, and location. Additional measure points can be randomly shifted, since they should have no influence on the solution. If desired, the random shifts can be sorted to produce a specific form error, such as a 3-lobed circle.

Generating reference data sets for non-least-squares cylinders requires more complicated mathematics. Reference data sets are not required for cones and tori because a geometrical tolerance cannot be applied to the resolved geometry of a cone or a torus, and the standards don't define conicity and toricity form tolerances. The mathematical description of the circularity tolerance of a sphere doesn't exactly match the Chebyshev sphere (sphericity), but the reference data set generation is included because they are so similar. Reference data sets for maximum inscribed and minimum circumscribed parallel planes are required because slots and tabs are subject to orientation and position tolerances and may be used as datum features, requiring a mating envelope calculation.

Besides testing the accuracy of the CMM software's non-least-squares fits, another consideration is whether or not the algorithm can find the global solution when multiple, local solutions exist. For most non-least-squares fits, a single, unique solution can be guaranteed by following some simple measurement rules. If these measurement rules are acceptable, then reference data sets with multiple solutions aren't required. Otherwise, reference data sets with multiple solutions should be specifically created. For each non-least-squares fit, simple methods are described to eliminate multiple solutions or to force them to exist.

2 Chebyshev Fit

The Chebyshev fit squeezes two features of perfect form together as closely as possible, while containing the measured points of the actual feature. The Chebyshev fit is used to calculate form tolerances because it minimizes the deviation of the measured feature from a feature of perfect form. For lines and planes, the two features of perfect form must remain parallel. For circles and spheres, the two features of perfect form must remain concentric, but the diameter may change.

The Chebyshev fit is stable when the force squeezing the two features together can no longer change the location and/or orientation of the two features of perfect form. For most features, a stable Chebyshev fit can be guaranteed to be unique simply by measuring the feature with evenly spaced points. The maximum number of measure points is determined by the form error relative to the size, or length, of the feature. The exception is the Chebyshev plane, which may commonly have two, stable solutions when measured in a grid pattern. For the other features, a reference data set with two independent, stable solutions can be constructed by forcing a point to be measured twice.

2.1 Chebyshev Line

A Chebyshev line fit squeezes two parallel lines about the measure points of an actual line until it contacts three points – two points on one line and one point on the other line, forming a triangle as shown in Fig. (1). If the two angles of the triangle on the side that contacts two points, θ_1 and θ_2 , are both less than 90° , then the Chebyshev line fit is stable to contraction. If one of these two angles is greater than or equal to 90° , then the two parallel lines can come closer together by rotating, losing contact with one of the points, but eventually contacting another point.

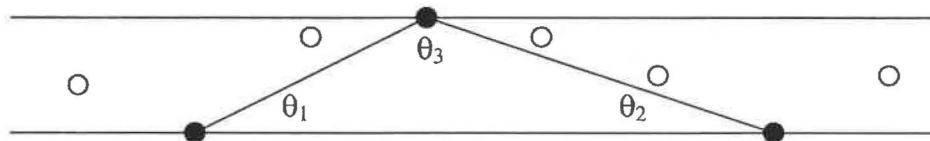


Fig. (1)

The Chebyshev line fit is unique if the angle of the triangle on the side with one point, θ_3 , is greater than or equal to 90° . Uniqueness can be guaranteed by restricting the number of evenly distributed measure points on the line to:

$$N < 4 \left(\frac{L}{d} \right)^2 \quad \text{Eq. (1)}$$

where N is the number of points, L is the length of the line, and d is the distance between the Chebyshev lines. For a straightness form error that is 10% of the length of the line, this allows 399 measure points, a condition that is easy to meet.

To construct a Chebyshev line reference data set that has a unique solution, start with a perfect, equally spaced line with N points, where N satisfies Eq. (1). Pick three random points on the line. Move the middle point a distance $d/2$ away from the line and move the other two points a distance $-d/2$ away from the line. For each of the other $N-3$ points, pick a random number, $-d/2 < r < d/2$, and move the point a distance r away from the line. These random deviations may be sorted, if desired, to produce a specific type of form error. The Chebyshev line solution is identical to the nominal line definition, with a separation distance of d .

A second solution for a Chebyshev line fit is extremely rare, requiring measurements to be repeated at the same location, and for the measurement uncertainty error at that point to dominate the form error of the line. To construct a Chebyshev line reference data set that has two solutions, start with a perfect, equally spaced line with $N-1$ points. Select a random point, n , and add an N th point at that location. Move the n th point a distance $d/2$ away from the line and move the N th point a distance $-d/2$ away from the line. For the other $N-2$ points, pick a random number, $-d/2 < r < d/2$, and move the point a distance r away from the line. Both Chebyshev line solutions contact points n and N , but the third contact point of each Chebyshev line solution has to be determined from the other measure points. The separation distances of the two solutions are different, but both will be slightly less than d .

A reference data set with two stable Chebyshev line solutions is shown in Fig. (2). The separation between the two points measured at the same location dominates the form error of the line. The Chebyshev line fit can pivot about these two points in two different directions, each leading to an independent, stable solution.

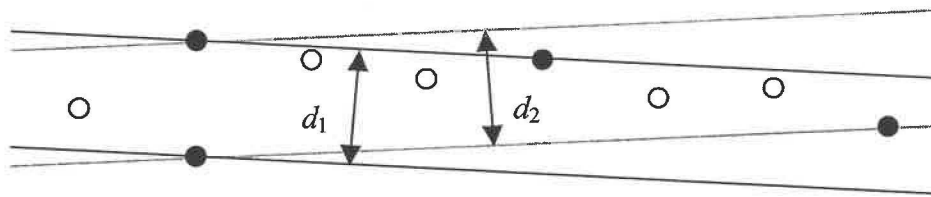


Fig. (2)

2.2 Chebyshev Plane

A Chebyshev plane fit squeezes two parallel planes about the measure points of an actual plane until it contacts four points – either three points on one side and one point on the other side (3-1) or two points on each side (2-2). Examples of these points of contact are shown in Fig. (3), where lines connect points that are on the same side. The 3-1 Chebyshev plane fit is stable to contraction if the single point is inside the triangle formed by the other three points. The 2-2 Chebyshev plane fit is stable to contraction if the two line segments cross each other. If these conditions aren't met, then the two parallel planes can come closer together by rotating, losing contact with one of the points, but eventually contacting another point.



Fig. (3)

The 3-1 Chebyshev plane fit is unique if the single point is at least a critical distance, ϵ , away from all three faces of the triangle. The 2-2 Chebyshev plane fit is unique if all four of the points are at least ϵ away from the intersection of the two line segments. The critical distance, ϵ , is a function of the form error of the plane and the length and width of the plane. The exact nature of this relationship is unimportant, since it is common for a point to be exactly in line with another pair of points, and zero is always less than ϵ . A second, stable solution for a Chebyshev plane fit is common, requiring only that three of the contact points be in line with each other. If a plane measured in a 3x3 grid pattern has a random form error, there is a 38% chance of two independent, stable Chebyshev plane fits existing.

To construct a Chebyshev plane reference data set that has a unique solution, start with a perfect, equally spaced rectangle with M points in each row and N points in each column. Pick four random points on the plane such that no three of the points are in line with each other. If the four points form a triangle that contains the fourth point, then this is a 3-1 Chebyshev plane. Otherwise, the four points form a 2-2 Chebyshev plane. The points contacting one side of the Chebyshev plane are moved a distance $d/2$ away from the plane and the other points are moved a distance $-d/2$ away from the plane. For each of the other $MN-4$ points, pick a random number, $-d/2 < r < d/2$, and move the point a distance r away from the line. These random deviations may be sorted, if desired, to produce a specific type of form error. The Chebyshev plane solution is identical to the nominal plane definition, with a separation distance of d .

There are a few measurement patterns that guarantee a unique Chebyshev plane fit, but they will almost never be used by a typical CMM operator. The square, 4-point pattern shown in Fig. (4) guarantees a unique solution because no line can be drawn that is within ε of touching 3 points. This can be extended to a circular pattern of measurement points, but this does a poor job of representing the interior of the plane. The 8-point measurement pattern shown in Fig. (4) adds an extra point in the middle of each triangle of the 4-point pattern, guaranteeing a unique solution. It becomes difficult to add more points to the pattern without forming three points in a line, especially while trying to maintain an even spacing between the points.

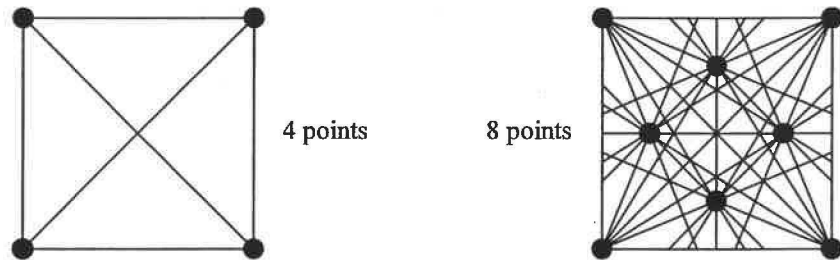


Fig. (4)

A second solution for a Chebyshev plane is common, since most planes are measured in a grid pattern, and 3-point lines can be found in each row, each column, and most diagonals. To construct a Chebyshev plane reference data set that has two solutions, start with a perfect, equally spaced rectangle with M points in each row and N points in each column. Select three random points that are in line with each other. Move the middle point a distance $d/2$ away from the plane and move the other two points a distance $-d/2$ away from the plane. For the other $MN-3$ points, pick a random number, $-d/2 < r < d/2$, and move the point a distance r away from the plane. Both Chebyshev plane solutions contact these three points, but the fourth contact point of each Chebyshev plane solution has to be determined from the other measure points. The separation distances of the two solutions are different, but both will be slightly less than d .

A reference data set with two stable Chebyshev plane solutions can be visualized by assuming that Fig. (1) is an end-on look at a plane, where the three points of contact are in line with each other. The vertical separation between the three points dominates the form error of the plane. The Chebyshev plane fit can pivot about this triangle in two different directions, each leading to an independent, stable solution.

2.3 Chebyshev Circle

2.4 Chebyshev Sphere

3 Minimum Circumscribed Fit

The minimum circumscribed fit squeezes a feature of perfect form as small as possible, while containing the measured points of the actual feature. The minimum circumscribed fit is used to calculate the size, orientation tolerance and position tolerance of an outer feature, such as a shaft or a tab, because it measures the smallest mating part that the feature fits inside. The minimum circumscribed fit is stable when the squeezing force can no longer change the location and/or orientation of the feature of perfect form. The minimum circumscribed fit should not be used on partial arcs of a circle or on partial hemispheres of a sphere because the answer is not very representative of the surface of the feature.

Except for parallel plane features, the minimum circumscribed fit is guaranteed to be unique. The minimum circumscribed parallel plane is not described here because the behavior is identical to the Chebyshev plane. Two independent, stable solutions are common with the minimum circumscribed parallel plane.

3.1 Minimum Circumscribed Circle

3.2 Minimum Circumscribed Sphere

4 Maximum Inscribed Fit

The maximum inscribed fit expands a feature of perfect form as large as possible, while inside the measured points of the actual feature. The maximum inscribed fit is used to calculate the size, orientation tolerance and position tolerance of an inner feature, such as a hole or a slot, because it measures the largest mating part that fits inside the feature. The maximum inscribed fit is stable when the expansion force can no longer change the location and/or orientation of the feature of perfect form. The maximum inscribed fit should not be used on partial arcs of a circle or on partial hemispheres of a sphere, because the feature expands to infinity.

Without restricting the placement of the measurement points, the maximum inscribed fit of a feature cannot be guaranteed, and it will be common for two independent, stable solutions to exist. The maximum inscribed parallel plane is not described here because the behavior is identical to the Chebyshev plane.

4.1 Maximum Inscribed Circle

4.2 Maximum Inscribed Sphere

5 Conclusions

Reference data sets can be easily generated using simple, geometric rules for Chebyshev fits of lines, planes, circles, and spheres, and for minimum circumscribed and maximum inscribed fits of circles, spheres, and parallel planes. For non-least-squares fits of a cylinder, more complicated mathematics is required to generate reference data sets. For non-least-squares fits where a second, stable solution is possible, the mechanisms that create a second solution can be explained using simple geometric concepts.

The minimum circumscribed fit of a circle or sphere is always guaranteed to be unique. The Chebyshev fit of a line, circle, or sphere rarely has a second, stable solution. The Chebyshev fit of a line, circle, or sphere can be guaranteed to be unique simply by requiring the measure points to be evenly spaced and not allowing a huge number of measure points.

The maximum inscribed fit of a circle or sphere, the Chebyshev fit of a plane, and the non-least-squares fit of a parallel plane commonly have a second, stable solution. By carefully controlling the placement of the measurement points, the uniqueness of these fits can be guaranteed. The maximum inscribed fit of a circle can be guaranteed to be unique if the circle is measured with an odd number (not too large) of evenly spaced measure points. For the maximum inscribed fit of a sphere and the non-least-squares fit of a parallel plane, the measurement patterns that guarantee uniqueness are more specific.

Testing CMM software using reference data sets that have a single, unique solution is sufficient for minimum circumscribed fits of circles and spheres, and for Chebyshev fits of lines, circles, and spheres. For maximum inscribed fits of circles and spheres, Chebyshev fits of planes, and the non-least-squares fits of parallel planes, however, CMM software should be tested with reference data sets that have a single, unique solution and with reference data sets that have two independent, stable solutions. Because the CMM operator may use a measurement pattern that does not guarantee a unique solution, the CMM software should be able to find the global solution in these cases.

AN IMPROVED B-SPLINE APPROACH FOR THE SURFACES RECONSTRUCTION FROM DATA MEASURED BY CMM

Franca Calì*, Edie Miglio°, Giovanni Moroni**, Marco Rasella**.

*Dipartimento di Matematica,

°MOX, Dipartimento di Matematica,

**Dipartimento di Meccanica.

Politecnico di Milano.

P.le Leonardo da Vinci 32, Milano, 20133, Italy

Abstract

The aim of this paper is the reconstruction of a surface starting from a cloud of points. In particular we tackle with a special kind of surfaces: kinematic surfaces. A coordinate measuring machine (CMM) measures the coordinates of the curve points. Contact probing devices, as CMM, provide an accurate, sensitive and reproducible indication, but there are still uncertainties associated with them. In this work measurement uncertainty and process errors are not estimated a priori but are considered as problem variables. The starting point is a set of measured data and to approximate this data we will use a λ -spline which is an integral B-spline depending on a parameter λ ; the value of this parameter affects the control points. From the computational point of view the construction of the λ -spline reduces to the computation of a linear combination of a classical B-spline and an integral B-spline. The weights of this linear combination are $(1-\lambda)$ and λ hence a suitable choice of λ is crucial to obtain a good approximation. An automatic optimization algorithm has been implemented to find the optimum value of λ to get the best approximating surface.

The algorithm is deeply discussed and some examples are presented to prove the effectiveness of the proposed method.

Keywords: kinematics surfaces, reverse engineering, quasi-interpolating spline, linear algebraic transformation

1. Introduction

In the traditional product development cycle, engineers transform a concept into a 3D model and, then, into real parts. In the iterative development process, the existing design is often modified on the shop floor due to manufacturing limitation or to obtain optimal product performance. Usually, such modifications are not reflected in the CAD model, so to update the existing geometry it is necessary to reconstruct the modified model. This process of reconstruction of a virtual model from an object is known as reverse engineering. Typically, it starts measuring a physical model or a prototype in order to acquire its geometric information in form of a three-dimensional set of points. These points are then subdivided into regions (segmentation); each of them represents a single geometric feature that can be mathematically represented by various surfaces. Finally, the surfaces are reconstructed and combined into a complete geometric model [1]. Digitization of an object can be achieved either by contact probing (e.g. touch trigger sensor on a CMM) or non-contact sensing techniques (e.g. laser beam). The latter are used for scanning 3-D dense measurement data in a short time, but the scanning result is not guaranteed due to some practical reason (e.g. reflective attributes and sharp areas of the surface, extraneous vibration of the system). Contact probing devices, as CMM, provide an accurate, repeatable and reproducible indication, but there are still uncertainties associated with them. Therefore, the measure has

to be expressed by a value and by an uncertainty estimate [2, 3]. A lot of work has been done to classify, determine [4] and reduce [5] those uncertainty sources. These uncertainty sources affect the subsequent shape design or shape evaluation. Therefore a correct and reliable method able to reconstruct the surface taking into account of these sources is needed. In the fields of computer graphics and computer aided design the problem of reconstruction of surface starting from a cloud of points is a well know problem and present different approach that differ from the application fields and from the starting data structure. In the surface reconstruction starting from contours the three-dimensional structure reconstruction start from stacks of two-dimensional contours. Although this problem has received a good deal of attention there remain several limitations with current methods. Perhaps foremost among these is the difficulty of automatically dealing with branching structures. Another field of interest is the surface reconstruction starting from data points produced by 3D laser range scanning system (3 D scanning), these scanning system produce large collections of points on surfaces of objects but they are unorganized, hence among them doesn't exist any topological relations. Some implemented method use a number of surface to approximate the real surface, but this number increase as the shape complexity increase. [6] [7] [8]. Some recent work addresses the problem of reconstructing smooth surfaces of arbitrary topological type using algebraic surfaces [9] [10]. However these smooth surface representations are not commonly supported within current modelling systems. The general class of non-uniform rational B-splines is considered by many the de facto CAD standard. So there has been considerable work on fitting B-splines surface to 3d points. However, most methods either assume that the surface has simple topological type as sphere plane [11] [12] [13] or require user intervention in setting up patch network [14] [15] [16] [17].

In this work, we deal with a particular class of surfaces: kinematics surfaces[18]. In this class we find all the surfaces that are generated by moving a curve along a path. So, if we consider a subgroups of motions (uniform helical, rotational or translation), a 2D curve and we apply the motion to the curve points we can obtain a cylindrical surfaces or a cylinder if the motion is a translation, a surface of revolution if the motion is a rotation about an axis and a helical surface otherwise. Therefore, to reconstruct these surfaces we need to reconstruct the path and the curve profile. In this work we deal with the curve profile reconstruction problem. A particular class of spline will be adopted (λ -spline) to reconstruct the curve used to generate the surface. This class of spline is an integral spline depending on a parameter λ . The value of this parameter, which is a real number, affects all the control points and hence the global curve shape. Namely, λ directly influences the shape of the corresponding spline curve. From a computational point of view the construction of the λ -spline reduces to the computation of a linear combination of a classical B-spline and an integral B-spline. The weights of this linear combination are $(1-\lambda)$ and λ , therefore a suitable choice of λ is crucial to obtain a fair shape. Some examples will illustrate the method.

2. Quasi-interpolating (q.i.) spline, integral q.i. spline and integral q.i. λ -spline.

Here we will briefly recall the definition of quasi-interpolating (q.i.) spline, integral q.i. spline and finally we will introduce the integral q.i. λ -spline.

It is well known that given a set of control point $P_0, P_1, \dots, P_m$ the equation for the q.i. spline ($S_m P$) can be written as follows:

$$(S_m P)(t) = \sum_{i=0}^m P_i B_i^k(t) \quad 0 \leq t \leq 1$$

where $B_i^k(t)$ are the B-spline basis functions associated with the nodes $t = (t_i)_{i=-k}^m$
 $0 = t_{-k} = \dots = t_0 < t_1 < \dots < t_n < t_{n+1} = \dots = t_{m+1} = 1$; moreover the following recurrence formula holds

$$B_i^k = \frac{t - t_{i-k}}{t_{i-1} - t_{i-k}} B_i^{k-1}(t) + \frac{t_i - t}{t_i - t_{i-k+1}} B_{i+1}^{k-1}(t).$$

On the other hand the integral q.i. spline $(T_m P)$ can be seen as a q.i. spline over a suitable modified set of control points (see [17])

$$(T_m P) = \sum_{i=0}^m M P_i B_i^k(t) \quad 0 \leq t \leq 1,$$

where

$$M = \begin{bmatrix} \beta_0 & \gamma_0 & & & 0 \\ \alpha_1 & \beta_1 & \gamma_1 & & \\ & \alpha_2 & \beta_2 & \dots & \\ & & \dots & \dots & \gamma_{m-1} \\ 0 & & & \alpha_m & \beta_m \end{bmatrix} \begin{cases} \alpha_0 = 0, \alpha_i = \frac{(\delta_i^l)^2}{2\Delta_{i-1}^k \Delta_i^{k+1}}, i = 1, \dots, m; \\ \gamma_i = \frac{(\delta_i^r)^2}{2\Delta_i^k \Delta_{i+1}^{k+1}}, i = 1, \dots, m-1, \gamma_m = 0; \\ \beta_i = 1 - \alpha_i - \gamma_i, i = 1, \dots, m \end{cases}$$

with $\Delta_i^k = \xi_{i+1}^k - \xi_i^k$, $\delta_i^r = \xi_{i+1}^{k+1} - \xi_i^k$, $\delta_i^l = \xi_i^k - \xi_i^{k+1}$, $\xi_i^{k+1} < \xi_i^k < \xi_{i+1}^{k+1}$ e $\xi_i^k = \frac{t_{i-k+1} + \dots + t_i}{k}$.

Finally the equation for the q.i. λ -spline can be written as follows

$$(T_m^\lambda P) = (1 - \lambda) (S_m P) + \lambda (T_m P) \quad (1)$$

where P is the set of control point derived from measured data. In the previous formula the contributions of the q.i. spline and of the integral q.i. spline is clearly evident.

The linear combination (1) shares the same properties of the $(S_m P)$ and $(T_m P)$ q.i. splines. As for the value of parameter λ it will be chosen in order to minimize a suitable quadratic functional.

3. Kinematics surfaces

A kinematics surface can be created by moving a two dimensional entity along a path.

Given the basis curve $(T_m^\lambda P)$, and a one-parameter subgroup $EM(t)$ of Euclidean motion [18] (uniform helical, rotational or translation) a kinematics surfaces is obtained by:

$$KS(T_m^\lambda P) = EM(t) (T_m^\lambda P) \quad (2)$$

4. Algorithm

Starting from a given motion path our kinematics surface reconstruction algorithm consist of three fundamentals steps, as show in Fig. 1.

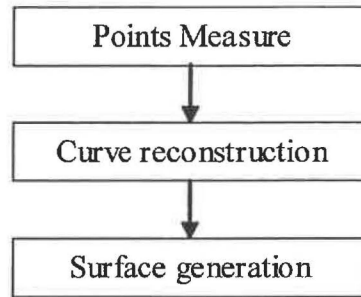


Figure 1 - Surface reconstruction algorithm.

First, a set of measured points has been detected by CMM. This set of points is considered to be located in a plane. Then, the curve profile is reconstructed using the measured points as control points of the λ -spline and the shape parameter (λ) is automatically optimized.

Finally, the kinematics surface is generated moving the reconstructed 2D profile along the relative path.

5. The quadratic functional and the minimization algorithm

Usually, in order to minimize the difference between the real part model and the reconstructed one, it must be take into account that measured points are not deterministic due to manufacturing inaccuracy and measurement uncertainty. Normally, this sources of errors are estimated a priori. In this work a similar result is obtained minimizing the following quadratic functional:

$$F(\lambda) = \sum_{i=1}^N \delta_i^2(P_i, T_m^\lambda P_i) \quad (2)$$

where δ_i is the distance between the control points and the corresponding points on the q.i. λ -spline.

To minimize (2) the method of Nelder and Mead has been used. This method is based on the following idea: for the minimization of a function of n variables this method starting from an initial guess $\mathbf{x}_0$ defines a simplex with $n+1$ vertices $\mathbf{x}_k = \mathbf{x}_0 + h_k \mathbf{e}_k$, $k=1, \dots, n$. During an iteration, the objective function is evaluated at each vertex of the simplex, and the vertex with the lowest value ($\mathbf{x}_{low}$), the vertex with the highest value ($\mathbf{x}_{hi}$) and the vertex with the next-to-highest value ($\mathbf{x}_{nexthi}$) are determined. Vertex $\mathbf{x}_{hi}$ is reflected through the centroid $\mathbf{x}_c$ of the remaining vertices to find a new vertex $\mathbf{x}_{refl}$ and the objective function is evaluated in the vertex $\mathbf{x}_{refl}$. Next a new simplex is constructed using only three possible transformations: *reflections* with respect to the centroids, *dilations* and *contractions* (for a detailed description of the algorithm see [19]). The stopping criterion requires that the standard deviation of the values $f(\mathbf{x}_0), \dots, f(\mathbf{x}_n)$ is less than a fixed tolerance ε .

6. Numerical results

In order to prove the effectiveness of the proposed approach, a preliminary testing phase has been conducted. Three test cases have been considered (Table 1): one is a profile of shoes sole produced by Finproject S.p.A., one is the profile of a mechanical part manufactured by a CNC lathe, installed in the Politecnico di Milano, Dipartimento di Meccanica laboratory, and its shape is a typically revolving geometry, the last profile is taken from a marble tile with a shape that is a typical extrusion geometry. For the measurements a Zeiss Prismo 5 MPS HTG coordinate measuring machine, equipped with VAST scanning probe and Calypso as control software, has been used.

First for each test cases a set of n_i points has been acquired, in particular for the marble tile three profile taken at different height has been analysed.

As for the optimization algorithm the following values for the parameters have been used: $\epsilon=10^{-4}$ and as starting point $\mathbf{x}_0 = 0$.

The following table presents the results obtained.

Test case	# measured points	λ	# of iterations
1	33	-0.443	22
2	203	1.7612	26
3a	338	0.0448	16
3b	338	-1.1738	25
3c	338	0.0188	13

Table 1: obtained experimental results

From these preliminary results we can draw the following main conclusion:

- Few iterations are necessary to converge;
- The third case shows that even for very similar data sets the optimal value of lambda can greatly vary, hence an heuristic procedure could be excessively time consuming;

7. Conclusion

A kinematics surface is generated by moving a 2D profile along a motion path. Therefore to reconstruct this class of surface a path and a profile have to be reconstructed. In this paper we tackle the problem of the curve profile reconstruction.

To solve the problem a particular class of spline (λ -spline) depending on a shape parameter has been considered. In order to minimize the difference between the reconstructed model and the original shape an optimization algorithm has been applied to find the optimal value of the shape parameter.

Acknowledgements

This work was carried out with the funding of the Italian M.I.U.R. (Ministry of Italian University and Research) and CNR (National Research Council of Italy).



Figure 2. Marble tile.

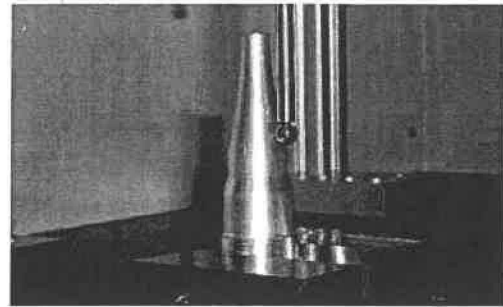


Figure 3. Mechanical part.

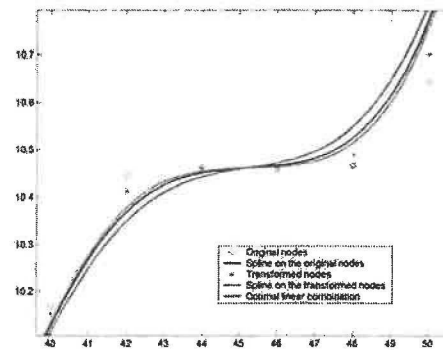
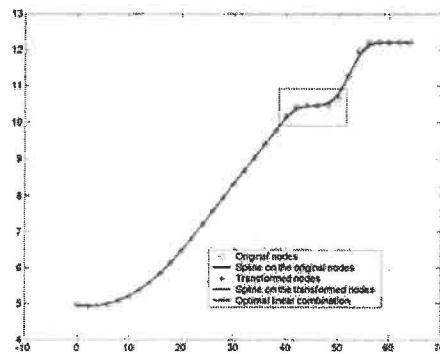


Figure 4. Case 1. Section of a rotation surface: whole curve (left) and zoom (right).

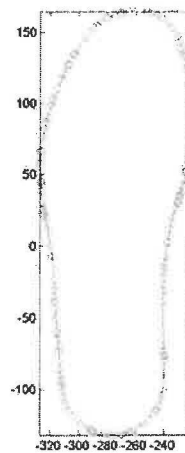


Figure 5. Case 2. Shoe sole profile: control points and reconstructed curve.

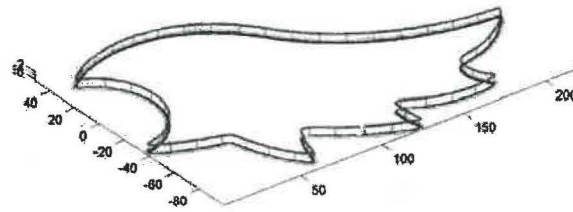


Figure 6. Case 3. Marble tile: reconstructed curves and whole surface.

8. References

- [1] T. Várady, R.R. Martin, J. Cox : "Reverse engineering of geometric models – an introduction", *Computer Aided Design*, vol.29, pp.255- 299, 1997.
- [2] ISO : "Guide to the Expression of Uncertainty in Measurement", *International Organization for Standardization*, Geneve, 1993.
- [3] ISO : "International Vocabulary of Basic and General Terms in Metrology", *International Organization for Standardization*, Geneve, 1993.
- [4] R.G. Wilhelm, R. Hocken, H. Schwenke : "Task specific uncertainty in Coordinate Measurements", *Annals of the CIRP*, vol. 50/2, pp. 553-563, 2001.
- [5] C. Menq, F.L. Chen : "Curve and surface approximation from CMM measurement data", *Computers Industrial Engineering*, vol.30, pp.211-225, 1996.
- [6] Curless, B., Levoy, M. A volumetric method for building complex models from range images. *Computer Graphics (SIGGRAPH '96 Proceedings)* (1996), 303-312
- [7] Hoppe, H., DeRose, T., Duchamp, McDonald, J., Stuetzle, W. Mesh optimization *Computer Graphics (SIGGRAPH '93 Proceedings)* (1993), 19-26.
- [8] Turk, G., Levoy, M. Zipped polygon meshes from range images. *Computer Graphics (SIGGRAPH '94 Proceedings)* (1994), 311-318.
- [9] Bajaj, C., Bernardini, F., Xu, G. Automatic reconstruction of surfaces and scalar fields from 3d scans. *Computer Graphics (SIGGRAPH '95 Proceedings)* (1995), 109-118
- [10] Moore, D., Warren, J. Approximation of dense scattered data using algebraic surfaces. *Proc. of the 24th annual hawaii Intl. Conf. on System Sciences*, Kanuai, HI, USA (1991), V. Milutinovic and D.Shriver, Eds., IEEE Comp. Soc. Press, 681-690
- [11] Hoschek, J., Schneider, F. -J., Wassum, P. Optimal approximate conversion of spline surfaces. *CAGD* 6 (1989), 293-306
- [12] Rogers, D., Fog, N. Constrained B-spline curve and surface fitting. *CAD* 21 (1989), 641-648.
- [13] Sarkar, B., Menq, C. -H. Parameter optimization in approximating method for surface fitting from sampled data. *Computer Graphics (SIGGRAPH '86 Proceedings)* 20 (1986), 179-188.
- [14] Andersson, E., Andersson, R., Boman, M., Elmroth, T., Dahlberg, B., Johansson, b. Automatic construction of surfaces with prescribed shape. *CAD* 20 (1988), 317-324
- [15] Fang, L., Gossard, D. Reconstruction of smooth parametric surfaces from unorganized data points. *Curve and Surfaces in Computer Vision and Graphics* 3 (1992), J.Warren, Ed., vol 1830, SPIE, pp. 226-236
- [16] Krishnamurthy, V., Levoy, M. Fitting smooth surfaces to dense polygon meshes. *Computer Graphics (SIGGRAPH '96 Proceedings)* (1996), 313-324
- [17] Milroy, M., Bradley, C., Vickers, G., Weir, D. G1 continuity of B-spline surface patches in reverse engineering. *CAD* 27 (1995), 471-478
- [18] H. Pottmann, T. Randrup : "Rotational and helical surface approximation for reverse engineering", *Computing*, vol.60, pp.307-322, 1998.
- [19] A. Quarteroni, R. Sacco, F. Saleri: "Numerical Mathematics", Springer-Verlag New-York, 2000

A Novel Ultra Precision CMM based on Fundamental Design Principles

Theo A.M. Ruijl

Philips Centre for Industrial Technology.
Eindhoven, The Netherlands.
t.a.m.ruijl@philips.com

Jan van Eijk

Delft University of Technology, Faculty of Mechanical Engineering, Advanced Mechatronics.
Delft, The Netherlands.
J.vaneijk@wbmt.tudelft.nl

1. Introduction

Nowadays, the functionality of products often requires parts with a geometric accuracy in the sub-micron range. The manufacturing process of such parts not only needs reliable and flexible production means, but also highly accurate metrology equipment. In order to perform measuring tasks with a large flexibility, a novel ultra precision coordinate measuring machine (CMM) has been developed and a prototype has been realised at the Centre for Industrial Technology (CFT) of Royal Philips Electronics. The machine has a measuring range of 100×100×40 mm and aims for a volumetric measuring uncertainty of 50 nm

2. Objectives of the Novel Ultra Precision Coordinate Measuring Machine

The design of the novel ultra precision coordinate measuring machine was driven by the following objectives:

- Volumetric measuring uncertainty of less than 50 nm;
- Measuring volume of 100×100×40 mm, where the plane of 100×100 mm corresponds with the horizontal plane;
- Overshoot of the machine axes after a probe trigger of less than 10 µm at an approach velocity of 1 mm/s;
- Maximum velocity of the individual machine axes of 10 mm/s;
- Ability to configure the measuring machine with different types of probes (e.g. 3D measuring probes, 1D surface scan probes).

Just as important as the actual realisation of the measuring machine was the acquisition and the development of knowledge about the design, geometric calibration and thermal behaviour of high precision machines. Hence the project also involves:

- Development of a calibration method and a compensation model to reduce geometric errors of the machine structure;
- Development of compensation models to reduce errors caused by environmental disturbances, especially thermally induced errors of the metrology frame.

The models have been implemented and preliminary evaluations show a remarkable error reduction. More about the calibration methods and thermal design considerations and compensation model will be given in following publications.

3. Main Design Considerations

Mechanical design aspects for precision instrument design are for example formulated by *Teague* and *Evans* (*Teague 1989*). Their so-called "patterns" give a comprehensive description of the main mechanical aspects to achieve a high positioning and measuring accuracy. Anyhow, the probably long list of patterns

and considerations to achieve a small positioning or measuring uncertainty can be categorised and assigned to three main objectives, namely:

1. High repeatability ("design for repeatability").
2. Small geometric calibration uncertainty ("design for calibration").
3. High predictability of the machine response to the main error sources ("design for predictability").

To satisfy these three main objectives, the following design considerations should be made:

- The alignment of the measuring systems should comply with the Abbe and Bryan principles (*Abbe 1890, Bryan 1979*). The relevant error motions of the slides should be measured. A proper alignment reduces the number of measuring systems, the amount of geometric calibration data, the calibration effort and the complexity of error compensation models.
- The structural and metrology functions should be performed with separate frames. That gives the opportunity to optimise the designs. The design of the metrology system should aim for a high stability, repeatability and predictability. It is important to distinguish the components which have to be stable during the time in-between calibrations (long term stability) and those components which only have to be stable during a single machine task (short term stability).
- Thermal effects are a large source of apparent non-repeatability of machine position and measuring accuracy (*Bryan 1990*). The metrology system should aim for a high thermal stability and a high predictability of the response to thermal distortions. Material selection, proper design of the geometric configuration and thermal insulation are important aspects to be considered.
- The dynamic requirements do not only concern the mechanics of the machine, but they concern the entire metrology and structural loop. With respect to the metrology loop of a coordinate measuring machine, this includes mainly: the metrology frame, the interaction between the probe and the workpiece and also the bandwidth of the measuring systems (e.g. data acquisition system).
- The ability and the uncertainty of geometric calibration of the metrology system. Using the machine itself to perform the calibration measurements means that the high stability and repeatability of the machine can be used to achieve a small calibration uncertainty. The use of error separation techniques should be considered to eliminate systematic errors of equipment and artefacts. The uncertainty analysis is an important part of the design phase and has to consider the machine as well as the calibration systems and methods.

4. Machine Concept

Various concepts have been evaluated with respect to the three main objectives as mentioned before (design for repeatability, calibration and predictability). Figure 1 shows the machine schematically, a photograph of the prototype of the ultra precision coordinate measuring machine is shown in figure 2. An enclosure is used to obtain a more uniform and stable temperature around the machine. The main subsystems of the machine are the metrology system and the manipulation system.

4.1 Metrology System

The mirror table, supporting the workpiece, is translated by means of the manipulation system (figure 1). The position (x,y,z) of the mirror table relative to the probe tip is measured with three remote plane mirror interferometer systems. The laser interferometer beam of the z -axis is pointing to the mirror table from below the manipulation system. The manipulation system is constructed around the laser beam of the z -interferometer axis. To comply with the Abbe principle, the functional lines of the laser interferometer axes are aligned with the centre of the probe tip. As the laser interferometers and the probe are all fixed to the metrology frame the alignment is maintained, independent of the measuring position. So, the Abbe principle is fulfilled for all three coordinate axes over the entire measuring volume. The metrology frame is kinematically attached to the base frame with elastic elements.

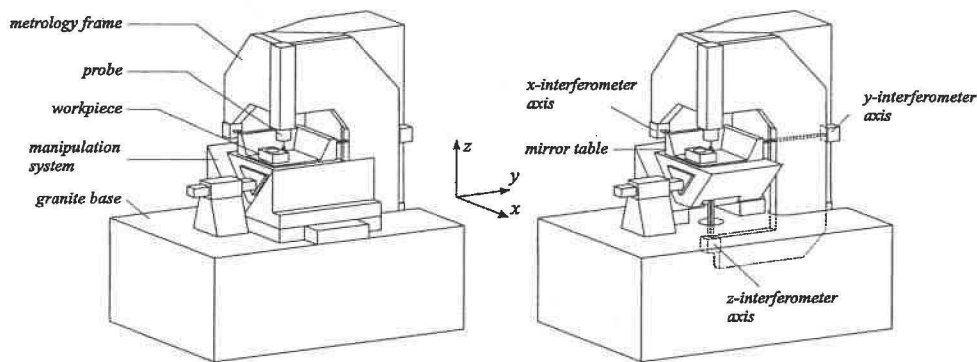


Figure 1: Schematic drawings of the ultra precision coordinate measuring machine. In the drawing on the right side, some parts of the manipulation system are removed to show the metrology frame and the position of the z-interferometer axis.

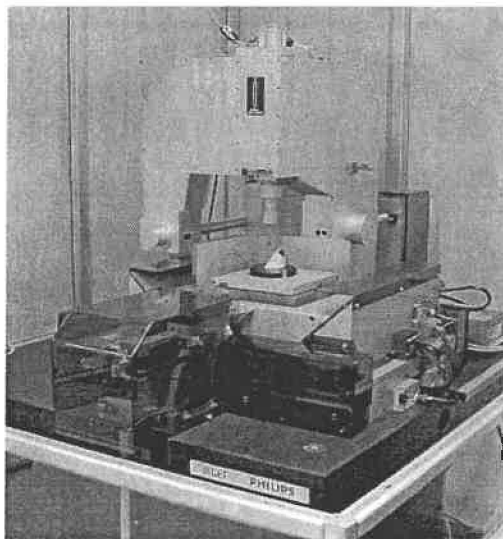


Figure 2: Photograph of the prototype of the ultra precision coordinate measuring machine placed in an enclosure.

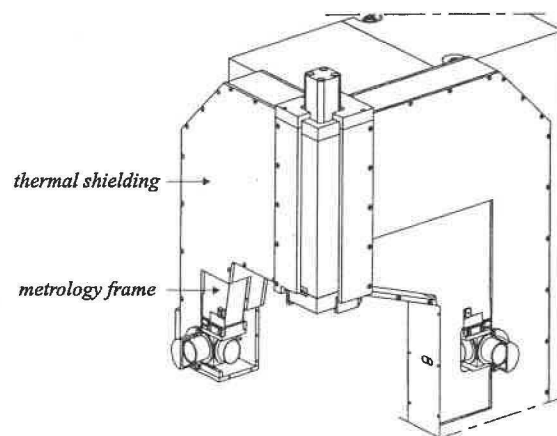


Figure 3: Thermal shielding covering the metrology frame.

The metrology frame consists of two plates, one containing the interferometer of the x-axis and one containing the interferometers of the y and z-axis. Both plates are connected by a column, to which the probe system is attached. As the Abbe principle is fulfilled, the metrology frame only has to transfer translational position information along the three interferometer axes. This means that such a simple straightforward frame, the assembly of the two plates and the column, is applicable.

One of the main goals of the research program was the development of thermal compensation models. Therefore the metrology frame is not made of materials like Super Invar or Zerodur. To increase the ability of reaching a small uncertainty of the thermal compensation model, the behaviour of the metrology frame should be predictable. Therefore a material with a high conductivity is used, namely aluminium, and a geometry with solid cross-sections, both giving a highly effective heat conductivity. Further, the frame is covered by a shielding. The usually very complex thermal boundary conditions are made less complex using this thermal shielding. Figure 3 shows a part of the metrology frame covered with the thermal shielding. The thermal shielding does not touch the metrology frame. The air gap between the thermal shielding and the metrology frame is about 5 mm.

A compensation model has been developed to compensate the thermally induced deformations of the metrology frame. The temperature distribution along the metrology frame is measured with 18 thermistors.

From these temperatures, the linear compensation model calculates the compensations along the x , y and z -axis. Analysis of the measuring uncertainty shows however, that the thermally induced deformation of the metrology frame is the main source of uncertainty. Using Zerodur or Super Invar instead of aluminium, will reduce the thermal expansion to several nanometers, making a compensation redundant. The shape of the metrology frame is very simple and the design details are feasible in Zerodur quite well.

4.2 Manipulation System

The main part of the structural frame is the manipulation system (see figure 4). The manipulation system translates the mirror table, supporting the workpiece. As illustrated in figure 1, the manipulation system is positioned on top of the granite base and is surrounded by the metrology system. A compact slide configuration with a high stiffness is developed. The slides are supported with air bearings, which are preloaded with vacuum. The outer-wedges can only translate in the x -direction along the guiding-beam. When both outer-wedges are moved in the same direction, the inner-wedge will translate in the x -direction. Moving both outer-wedges in opposite direction, gives a translation of the inner-wedge in the z -direction. In order to translate the inner-wedge in the y -direction, the y -slide is moved along the y -axis and the inner-wedge is guided in the large v-groove formed by both outer-wedges. The lowest eigenfrequency of this slide configuration is about 250 Hz.

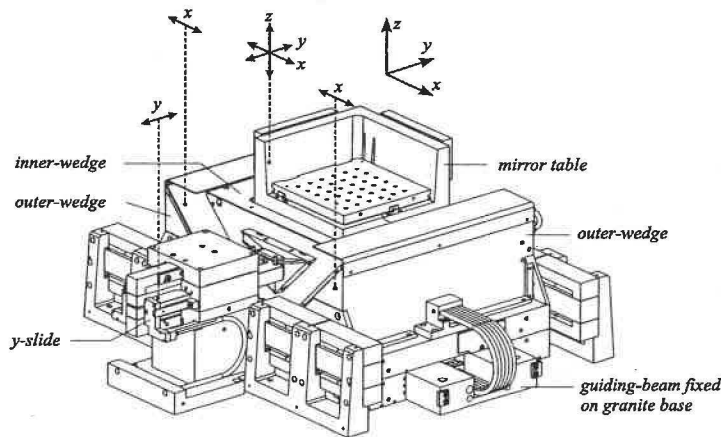


Figure 4: Manipulation system translating the mirror table along the x , y and z -axis.

The slides are driven with Lorentz-actuators according to the direct-drive principle. The combination of low drive forces (y -actuator: 2 N; xz -actuators: 5 N) and relatively small strokes (y -actuator: 100 mm; xz -actuator 140 mm) makes it possible to apply these simple actuators without commutation. The simple design of the actuators can be integrated into the slides to a large extent, keeping the slide configuration very compact.

A pneumatic weight compensation system has been applied to minimise the heat generation of the actuators. The pneumatic system compensates the total weight of the components moving along the gravitational axis (z -axis), including the weight of the workpiece. The actuators only have to deliver the slide actuation forces (about 5 N) instead of the weight of the inner-wedge, which can be 130-200 N depending on the workpiece weight. So, heat generation is reduced considerably and significantly smaller actuators can be used.

To obtain an automatic adjustment of the compensation force depending on the weight of the workpiece, the pneumatic compensation system is integrated in the servo system. The static component of the z -drive force quantifies the mismatch between the actual weight and the compensation force. Therefore, the force of the z -drive is used as a feedback signal for the weight compensation loop.

5. Geometric Calibration

The geometric calibration of the machine involves, besides the wavelength of the laser interferometer system, only the flatness deviations and out-of-squareness of the three mirrors of the mirror table. Since the geometric stability of the mirror table has to be guaranteed in the time between calibrations (long term stability), the mirror table is manufactured out of Zerodur.

The change in path length of a remote plane mirror interferometer due to a displacement of the measurement mirror given by a vector $\vec{R}$ (see figure 5) is

$$\Delta L_{path} = 4(\vec{n} \cdot \vec{R})(\vec{n} \cdot \vec{i}) \quad (1)$$

Where the outer normal unit vector of the measuring mirror is defined by $\vec{n}$ and the direction of the incident laser beam by the unit vector $\vec{i}$.

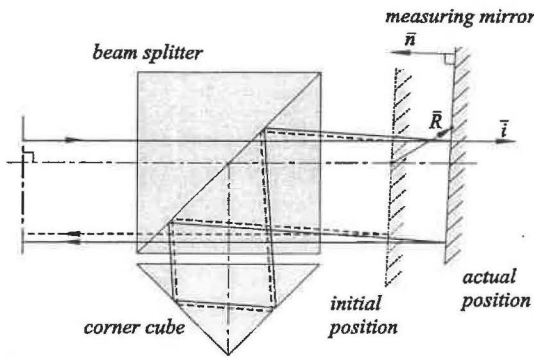


Figure 5: Beam path through a plane mirror laser interferometer when a tilted measuring mirror is translated. Only the measuring beam is drawn.

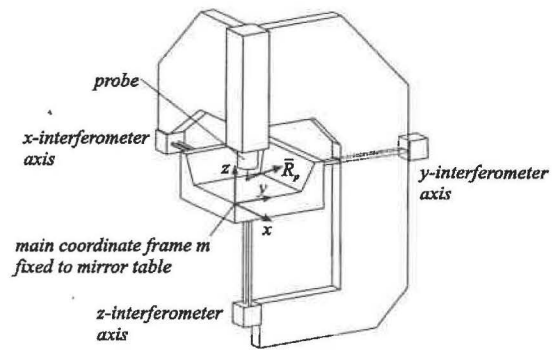


Figure 6: Metrology system of the ultra precision coordinate measuring machine and the main coordinate frame m of the machine fixed to the mirror table.

From equation (1) follows that the functional direction (sensitivity direction) of a remote plane mirror laser interferometer is the mirror normal $\vec{n}$. A misalignment of the laser beam relative to the mirror normal introduces a scale error, equal to $1 - |\vec{n} \cdot \vec{i}|$. Note that an angular misalignment of $100 \mu\text{rad}$ results in a sub nanometer measurement error considering the given measurement ranges. Therefore, no further attention is paid to that small scale error and we assume that $(\vec{n} \cdot \vec{i}) = -1$.

Considering equation (1) with $(\vec{n} \cdot \vec{i}) = -1$ for the three measuring axis, we obtain the linear transformation between the translation of the probe tip centre and the three measurement positions of the laser interferometer systems. Given the main coordinate frame $^m\{x, y, z\}$ of the machine fixed to the mirror table (see figure 6), the translation vector $\vec{R}_p$ of the probe tip centre from position 0 to 1, represented by the column matrix $^m[\Delta x_p, \Delta y_p, \Delta z_p]_{0,1}^T$, is given by the linear transformation

$$^m \begin{bmatrix} \Delta x_p \\ \Delta y_p \\ \Delta z_p \end{bmatrix}_{0,1} = \begin{bmatrix} ^m \mathbf{n}_x^T \\ ^m \mathbf{n}_y^T \\ ^m \mathbf{n}_z^T \end{bmatrix}^{-1} \begin{bmatrix} [x_{L,1} + h_x^{cal}(y_{L,1}, z_{L,1})] - [x_{L,0} + h_x^{cal}(y_{L,0}, z_{L,0})] \\ [y_{L,1} + h_y^{cal}(x_{L,1}, z_{L,1})] - [y_{L,0} + h_y^{cal}(x_{L,0}, z_{L,0})] \\ [z_{L,1} + h_z^{cal}(x_{L,1}, y_{L,1})] - [z_{L,0} + h_z^{cal}(x_{L,0}, y_{L,0})] \end{bmatrix} \quad (2)$$

Where the column matrices $^m \mathbf{n}_x$, $^m \mathbf{n}_y$, $^m \mathbf{n}_z$ represent the outer unit normal vectors of the corresponding mirrors in the main coordinate frame m . The calibrated mirror flatness deviations of the x , y and z -mirrors are defined by $h_x^{cal}(y_L, z_L)$, $h_y^{cal}(x_L, z_L)$ and $h_z^{cal}(x_L, y_L)$, and measurement positions of the interferometers by x_L , y_L and z_L .

To establish the mirror flatness deviations ($h_x^{cal}(y_L, z_L)$ etc.) and the out-of-squareness (defining the outer unit normal vectors ${}^m\mathbf{n}_x$ etc.), calibration methods are developed. In order to obtain a very small calibration uncertainty, the calibration measurements are performed with the machine itself.

To achieve a calibration uncertainty that is not influenced by the uncertainty of artefacts, the calibration methods are based on error separation techniques. The mirror flatness calibration uses an artefact with a plane and a line. The out-of-squareness calibration is also based on an error separation technique. An artefact (polygon) with four faces is measured in four orientations. The propagation of the individual measuring uncertainties in the geometric calibration methods is investigated. It appears that the unidirectional geometric calibration uncertainty of the z -axis is less than 6 nm. Along the x and y -axis the unidirectional geometric calibration uncertainties are less than 8 nm. The volumetric geometric calibration uncertainty appears to be less than 14 nm.

6. Conclusions

Summarising we may conclude that, based on very important principles of precision machine design, a new concept of a coordinate measuring machine has been developed. The design aims for a high measuring repeatability, a high predictability of the machine response to the main error sources and the ability to reach a small geometric calibration uncertainty. The number of measuring systems is minimised to three and the geometric calibration involves only a single machine component. The feasibility of the design has been demonstrated and the main principles and performance have been evaluated experimentally. Although the thermally induced deformations of the metrology loop are compensated, they are still the largest source of measuring uncertainty. Mainly determined by the experimentally investigated geometric calibration uncertainty and thermal compensation uncertainty, a unidirectional measuring uncertainty of 22 nm is estimated. The estimated volumetric measuring uncertainty is 27 nm.

References

1. Abbe E., 1890, 'Meßapparate für Physiker', *Zeitschrift für Instrumentenkunde*, 10. (In German)
2. Bryan J.B., 1979, 'The Abbe Principle revisited: An Updated Interpretation', *Precision Engineering*, No. 3.
3. Teague, E.C. and C. Evans, 1989, 'Patterns for Precision Instrument Design (Mechanical Aspects)', NIST Tutorial Notes, ASPE Annual Meeting, Norfolk, Virginia.
4. Bryan J.B., 1990, 'International Status of Thermal Error Research', *CIRP Annals*, Vol. 39/2.

Design of a 3D-Coordinate Measuring Machine for measuring small products in array

J.K.v.Seggelen¹, P.C.J.N. Rosielle¹, P.H.J. Schellekens¹, H.A.M. Spaan², R.H. Bergmans³

¹Precision Engineering section of the Faculty of Mechanical Engineering, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

²IBS Precision Engineering bv, Bedrijfsweg 1, 5683 CM Best, The Netherlands

³NMi Van Swinden Laboratorium, P.O. Box 654, 2600 AR Delft, The Netherlands

e-mail address corresponding author: J.K.v.Seggelen@tue.nl

Abstract

This paper describes the machine lay-out of a scale based stand-alone design, presently under construction, aimed at an accuracy of 25 nm in a $50 \times 50 \times 4$ mm³ volume. The scales have 1 nm resolution and are direct driven by single phase, linear DC motors. In the horizontal plane an air bearing guide system is used with separate stress frames for bearing pre-load forces. The elastically guided vertical z-axis has 4 mm stroke and is measuring in Abbe. It is thermally-, weight- and stiffness compensated and mounted statically determined on the x, y scale carrying beams. Compared to CMMs with a vertical air bearing guide system, the mass of the guides and their vertical drive offset was reduced significantly. A large improvement in system dynamics features a lowest eigenfrequency (rotation mode around the z-axis) of about 60 Hz. The uncertainty of a volumetric length measurement, due to residual geometric errors, will be about ± 20 nm.

Introduction

To allow high speed scanning of MST products, small products in array set-ups and laboratory measurement tasks for calibration purposes of single objects, precision 3D coordinate measuring machines are highly flexible automated machines. Constant development of both touch probes⁵ and machines^{2, 3, 4, 6} is going on in industry and in research institutes. While the latter developments sometimes consists of "machine in machine"⁴ set-ups where laser interferometry is used to realise extreme accuracy, industrial designs often use scales. This paper describes the machine layout of a scale based stand-alone design, aimed at an uncertainty of 25 nm in a $50 \times 50 \times 4$ mm³ volume. Figure 1 shows the schematic of the x y motion in top view.

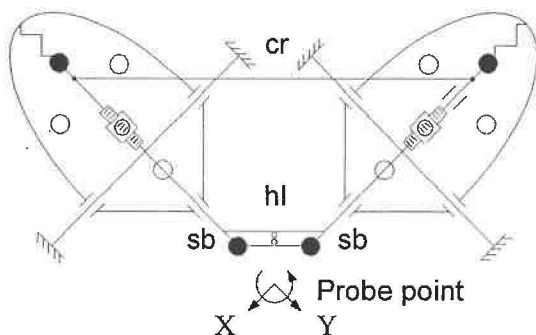


Figure 1: x, y system schematic top view

The x, y- system of figure 1 differs from that of [2] in that there are now four z-bearings (black dots), one at each end of a scale beam. The probe near end of the scale beams sb is connected by two hinged leaf springs hl (one visible, the other one below that). A connecting rod cr links the remote end of the scale beams. The internal degree of freedom avoids over constraint of four z-bearings.

Description

The machine base consists of a base plate 2a (= a in figure 2) in which a pattern p with a depth of 50 mm is milled. Next three blocks (one square 2b and two rectangular 2c and d) are connected to the bottom plate. The moving parts (figure 3 and 4) are supported on the topsides of the three blocks 2 b c d. The bottom surfaces of the blocks, which overlap the pattern in the bottom plate, are used to pre-load the air bearings of the moving parts in z-direction.

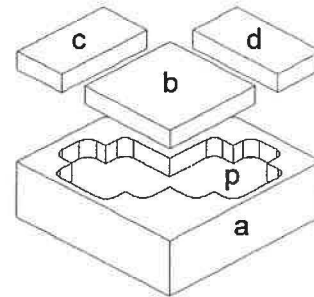
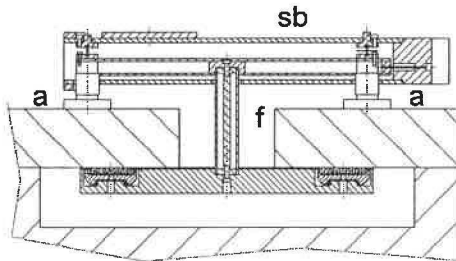


Figure 2: Machine-base



The pre-load is lead directly above the bearings 3a in z-direction of the moving bodies by one pre-load force frame 3f for a scale beam 3sb and two 4f for an intermediate body.

Figure 3: scale beam cross section with internal pre-load force frame

An intermediate body is equipped with four bearings 4a in z-direction. This made it possible to build low because the bearings in z-direction and their matching alignment bodies b can countersink into the moving bodies. The bearings in z-direction of an intermediate body, which are the most far from the probe a', are connected to the intermediate body with an elastic line hinge 4h to make sure that the support doesn't become over constrained. Two sides of the square block 2b function as an angle standard, guiding the air bearings 4c of the intermediate bodies.

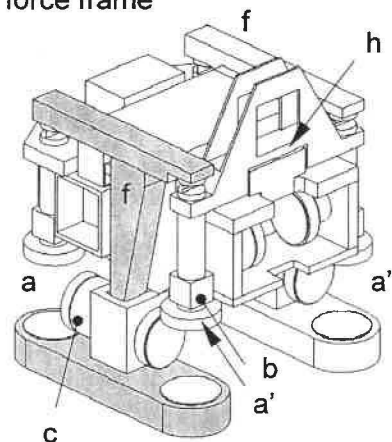
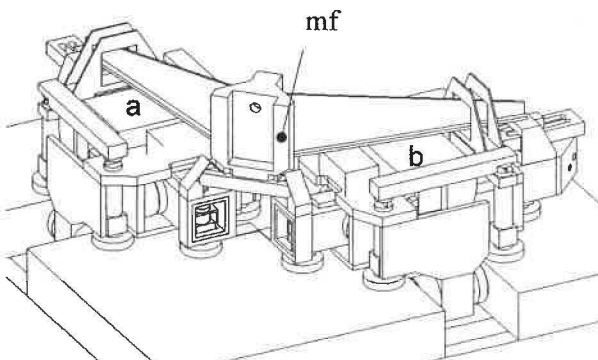
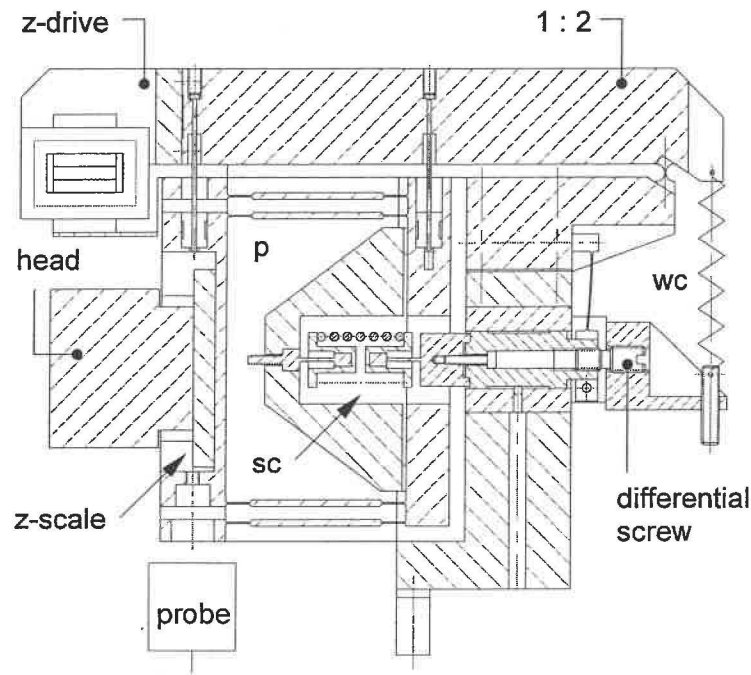


Figure 4: One of two intermediate bodies with statically determined mounted pre-load frames 4f



The mounting face mf, which carries the z-axis, is connected statically determined on the z-bearings of the x, y scale carrying beams (figure 5).

Figure 5: Mounting platform for z-axis statically determined on scale beam bearings to avoid bending



The z-axis is thermally- (by double parallelogram p), weight- (by weight compensation spring wc) and stiffness (by stiffness compensation spring sc) compensated. The probe and z-scale are aligned thereby measuring in Abbe.

Figure 6: The elastically guided vertical z-axis, 4 mm stroke, weight- and stiffness compensated, measuring in Abbe.

Data summary

- Size of the Aluminum machine is about $450 \times 450 \times 200 \text{ mm}^3$ supported on a base of about $535 \times 535 \times 200 \text{ mm}^3$
- Thermal loop 150 mm
- Measurement loop 125 mm
- Mass of a scale beam is estimated to be 1,5 kg at a c.o.g. distance of 190 mm from the z-axis
- Mass of an intermediate body is estimated to be 4 kg at a c.o.g. distance of 190 mm from the z-axis
- Mass of the elastically guided z-axis is about 1,5 kg, moving mass: 0,12 kg
- Moment of inertia about the z-axis is estimated to be $0,2 \text{ kg} \cdot \text{m}^2$
- Lowest eigenfrequency is about 60 Hz (rotation mode around the z-axis)
- Eigenfrequency of the probe in z-direction is about 180 Hz

Error modeling

The procedure to map the geometric errors is almost the same as the one, which is described in [2] (page 62 to 104). There will be a small difference between the total error vectors of both machines because the guiding surfaces of this CMM are placed below the horizontal guiding surface.

The total error vector of the CMM results from the sum of the individual error vectors of the moving bodies of this CMM (Intermediate body A and B of figure 5, mounting face MF of figure 5 and z-mechanism Z of figure 6) and the squareness errors between the guide systems for x, y and z.

$$d\bar{P} = d\bar{P}_A + d\bar{P}_B + d\bar{P}_{MF} + d\bar{P}_Z + d\bar{P}_s$$

$$d\bar{P} = \begin{bmatrix} {}_B T_x + {}_B R_y \cdot L_{\text{scale } x - \text{guiding surface}} + {}_{MF} T_x + {}_Z T_x + ({}_{MF} R_y + {}_x S_z) \cdot z \\ {}_A T_y - {}_A R_x \cdot L_{\text{scale } y - \text{guiding surface}} + {}_{MF} T_y + {}_Z T_y + {}_{Gb_A} S_{Gb_B} \cdot x - ({}_{MF} R_x - {}_y S_z) \cdot z \\ {}_{MF} T_z + {}_Z T_z \end{bmatrix}$$

The errors in this vector are position dependent and can be calibrated and compensated with software. A realistic estimation of the expanded uncertainty (2σ) of a length measurement is about: $1 \text{ nm} + 1\text{E-}7 \cdot L$ (L is the measuring length in nm) and a realistic estimation of the expanded uncertainty of an angular measurement is about: $0,05'' = 0,25 \mu\text{rad}$. Estimations of the residual uncertainties after calibration of these thirteen errors are presented in table 6.1, in [7]. With this data the expanded uncertainty of a volumetric length measurement ($2\sigma_{xyz}$), due to uncorrected residual geometric errors, will be about 20 nm.

References:

- [1] Keynote paper, session P CIRP 48 th General Assembly Athens Greece 1998 volume 47/2
- [2] Vermeulen, M.M.P.A., High Precision 3D-Coordinate Measuring Machine, Design and Prototype-Development, Ph.D. thesis, section Precision Engineering, Fac. of Mech. Eng., Eindhoven University of Technology, The Netherlands, 1999 (in English)
- [3] A. Jansen, P.C.J.N. Rosielle, P.H.J. Schellekens, A fully elastically guided 3D CMM with a measuring volume of 1 cm^3 , section Precision Engineering, Fac. of Mech. Eng., Eindhoven University of Technology, The Netherlands, 1999 ASPE Annual Conference Proceedings volume 20 p 452-455
- [4] Peggs, G.N., Advanced CMM design, invited paper National Physical Laboratory, 1999 Proceedings volume 20 ASPE
- [5] Pril, W.O., Haitjema, H., Schellekens, P.H.J., A silicon-etched probe for 3D CMMs with an uncertainty below 0.1 micrometer, Proceedings symposium on Micro technology in Metrology an Metrology in Microsystems, 31-8/1-9, Delft, ISBN 90-90 12166-9
- [6] Ruijl, T.A.M., Ultra Precision Coordinate Measuring Machine, Design Calibration and Error Compensation, PH.D. thesis, Philips Centre for Industrial Technology Eindhoven, The Netherlands
- [7] Van Seggelen, J.K., Design of a 3D-Coordinate Measuring Machine for measuring small products in array setups, Masters thesis, section Precision Engineering, Fac. of Mech. Eng., Eindhoven University of Technology, The Netherlands, 2002 (in English)

A Modular, Multiple Sensor Embedded System CMM Motion Controller

David W. Chang^a, Peng Wu^a, John O. Harris^a, John E. Peterson^b, Joe Heslip^b, Allan D. Spence^{a,*}

^aMcMaster University, Hamilton, ON, L8S 4L7, Canada

^bOmni-Tech Corporation, Fenton, MI, 48430, USA

Abstract

This paper describes design, development, and implementation of an embedded system style CMM controller. A single Intel Pentium microprocessor performs all functions including real time motion control. Boot up is via a solid state IDE flash disk to the Phar Lap ETS real time, multi-threaded operating system. An FTP server is always active. Hence configuration parameters, and even the main executable, can quickly be replaced. Setup is performed using a special GUI program that is executed on a notebook computer attached via 100BaseTX Ethernet. Graphing of commanded and actual position, commanded velocity, etc. is available in real time. Tuning parameters can be changed and their effect observed on the fly.

A significant issue with new sensors is combining the CMM structure error compensation with that of the sensor. Experience with this combination is reported for a Hymarc laser digitizer. The CMM structure was equipped with thermocouples on each axis, the granite table, and the probe mount. Error compensation tables were then created at 20, 25, and 30 degrees Celsius. A special ball bar, with optically diffuse coatings on the spheres, was then located at the 20 ASME B89.4.1-1997 positions to evaluate the combined CMM structure and laser digitizer error compensation transformations. An average 75 percent reduction in ball bar length dispersion was obtained.

Keywords: Motion control; Embedded system; Laser digitizer; Error compensation

1. Introduction

A background of CMM technology is described in [1]. For a bridge style CMM, the main components include the granite table, the moving bridge and related structure, and a linear scale encoder system. Conventionally, a touch trigger probe is used to measure the part surface. When the probe touches the part, it deflects and opens an electrical switch. This latches the scale position within an integrated circuit counter. The CMM control computer adds any probe and geometric error compensation [2], and transmits the measured data to a higher level metrology software computer. For a Direct Computer Controlled (DCC) machine, electric motors and associated drive components are added so that, additionally, motion can be commanded from the metrology software. The metrology software provided by the CMM vendor is proprietary, and typically not portable. Support for new sensors requires significant upgrade to the CMM control, possibly including total replacement. This situation is awkward for the CMM owner, and hinders rapid and cost effective adoption of emerging measurement technologies.

To address these issues, the industry is again moving towards widespread adoption of the Dimensional Measuring Interface Standard (DMIS) [3] to interface Computer Aided Design (CAD) software with the CMM metrology software. The I++ proposal [4] is intended to provide a standard interface protocol between the metrology software and the CMM controller. For sensors, the Optical Sensor Interface Specification (OSIS) [5] is being developed. To meet these new requirements, it is neither economically sensible nor environmentally appropriate to replace a working machine. Instead, a CMM controller upgrade solution compatible with legacy applications but extensible to support new software and sensors is preferred.

The concept of open architecture control is well established, particularly for Computer Numerical Control (CNC) of machine tools [6]. Research implementations for CMMs include the NIST Enhanced Machine Controller, which can be programmed using DMIS [7]. Industrial aftermarket CMM controllers include the Renishaw UCC1 [8]. The Next Generation Inspection Systems (NGIS) project included specification of a Sensor Interface Module (SIM) and Application Programming Interface (API) for CMM sensors [9], but has not been widely adopted.

Omni-Tech Corporation offers the OTC5000 controller, and to date approximately 100 units of this product have been commercially installed. In conjunction with McMaster University, the second generation controller design has been developed and implemented. A description of this work is the subject of the remainder of the paper.

* Corresponding author. Tel.: 1-905-525-9140 Ext. 27130; Fax: 1-905-572-7944.

E-mail address: adspence@mcmaster.ca (A.D. Spence).

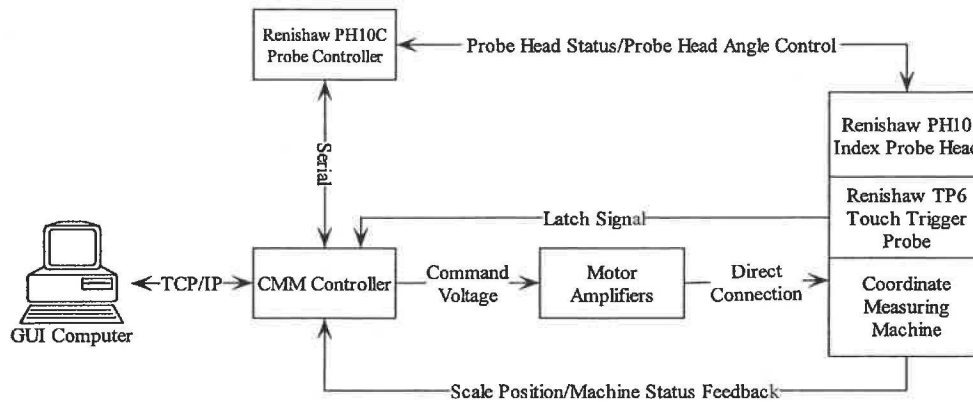


Fig. 1. CMM touch probe system architecture. The touch trigger probe architecture is shown. For an analog probe, the TP6 is replaced by an SP600 and a multiwire cable leads back to an AC2 interface card at the controller.

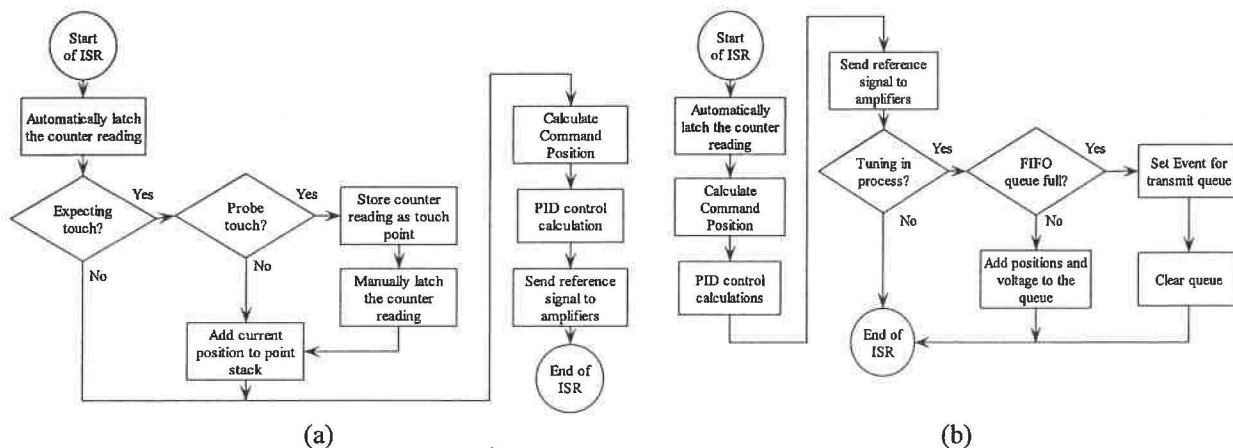


Fig. 2. CMM software ISR flowcharts: (a) normal touch trigger probe operation; (b) motion control tuning.

2. System Architecture

2.1. Hardware

An overall system architecture schematic for the CMM controller is shown in Fig. 1. The CMM used for the initial implementation was a DEA IOTA 1102 with a Z on Y on X on granite table moving bridge configuration. Each axis is driven by pulse width modulated (PWM) amplifiers, rotary DC motors, and rack and pinion gearing. Motion control velocity feedback is provided by tachogenerators, and Renishaw RGH22 linear scales are used for one micrometer resolution position feedback. The touch trigger probe is a Renishaw TP6A mounted on a PH10M probe head. An SP600M analog probe with AC2 interface card [10] can be substituted. Non-contact laser digitizer interfacing is discussed below. A 133 MHz Intel Pentium I standard ISA/PCI motherboard with 64MB RAM was used. To avoid failure due to shock of vibration, a 16 MB IDE compatible flash disk is used for non-volatile storage. Because the controller is intended for used as an embedded system, RS-232 serial and 100BaseTX Ethernet are used for communication with the metrology interface computer. To simplify installation and remote maintenance, firmware upgrades are made using TCP/IP File Transfer Protocol (FTP).

Electrical interface to the CMM is via an 8 axis motion interface card [11]. This card provides 24 bit axis counters (extended to 32 bits in software), 13 bit analog to digital (A/D) input and digital to analog (D/A) output, as well as 32 bits of general TTL level input/output (I/O). The CMM linear scales are connected to the counters, the manual control joysticks are connected to the A/D inputs, and the motor amplifiers are driven by the D/A outputs. Additional multiplexing and buffering electronics connect the TTL I/O to limit switches, manual pushbutton switches, compressed air solenoid and pressure switch, etc. Probe debounce is implemented by connecting the normally closed switch touch trigger switch to an edge triggered D flip-flop that is in turn connected to the axis counter latch input. When trigger switch opens, the flip-flop output changes state. Time latency is negligible. To ensure that only the initial probe contact position is latched, a software re-arming of the flip-flop is required. For

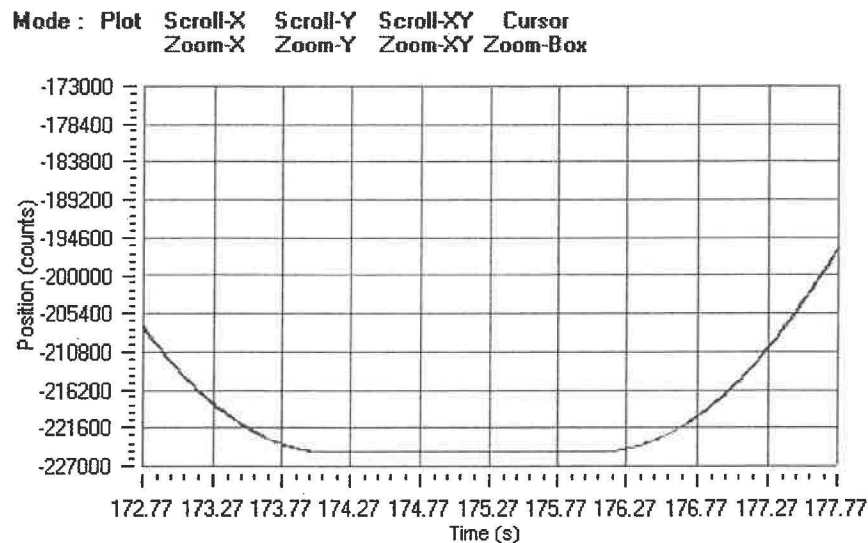


Fig. 3. X-axis tuning strip chart.

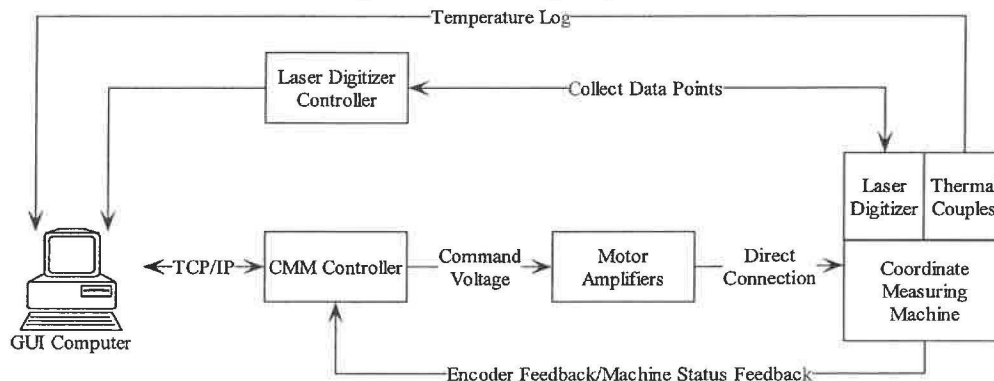


Fig. 4. CMM non-contact laser digitizer system architecture.

the analog probe, the analog deflection voltages are transmitted over a multiwire cable connected to a Renishaw AC2 A/D conversion card. The axis scale counters are latched and combined with the analog deflection voltages to obtain the actual part surface coordinates. For elevated temperature compensation, 11 type-E thermocouples are used. One thermocouple was attached to the granite table, one to the probe head, and 3 to each linear scale.

2.2. Software

The CMM controller software is based on the VenturCom Phar Lap ETS real time operating system [12]. After power up, the computer boots the ETS operating system from the flash disk, and then runs the CMM specific executable. An FTP server is included so that implementation specific startup parameters, motion tuning information, geometric error compensation tables, and even the executable itself can be updated by simply uploading the replacement file and rebooting. Separate execution threads handle RS-232 serial and TCP/IP Ethernet communication, probe and joystick monitoring, FTP commands, etc. Real time motion control uses interrupts generated by an 800 microsecond timer. As a safety precaution, a "watch dog" timer is included. Should the Interrupt Service Routine fail to reset the timer, the D/A outputs to the motor amplifiers are automatically set to zero volts.

The main program thread receives the OTC5000 [13] language command. Motion command profiles are pre-calculated just prior to real time execution. For a single point to point position move, a trapezoidal velocity profile is calculated. For joystick input, a velocity move with constant acceleration is used. Multi-point (DMIS GOTARG) contouring moves include constant acceleration at all interior corner points. Fig. 2(a) shows a condensed flowchart of normal touch trigger probe operation. Unless a touch is expected, the hardware automatically latches the counters when the interrupt occurs. If the controller is expecting a touch, it will latch the counters in real time when the touch

actually occurs. To maintain consistent sample time spacing, the counters are again latched in software before the motion control algorithm is executed.

For each axis, a conventional Proportional-Integral-Derivative (PID) control law, with velocity and acceleration feed forward, is used to execute the real time motion. At the end of the ISR sample period n , the controller executes the PID update equation

$$O_n = K_R(K_p E_n + K_d(E_n - E_{n-1}) + K_i S_n + K_v V_n + 64 K_a A_n) + K_o$$

where

O_n	is the motor control output voltage	K_R	is the overall scale factor ($K_R = 2^{\text{shift}}$)
K_p	is the proportional gain	K_i	is the integral gain
K_d	is the derivative gain	K_v	is the velocity feed forward
K_a	is the acceleration feed forward	K_o	is the static offset
E_n	is the position error	V_n	is the command velocity
A_n	is the command acceleration ($\times 2^{-6}$)	S_n	is the integrated error,
$S_n = \begin{cases} S_{n-1} + E_n & \text{if } -S_{\max} < S_n < S_{\max} \\ S_{\max} & \text{if } S_n > S_{\max} \\ -S_{\max} & \text{if } S_n < -S_{\max} \end{cases}$		$S_{\max}$	is the maximum integrated error

During joystick operation, the A/D inputs are polled, and motion occurs using the same PID method. This allows consistent choice of velocity and acceleration parameters for both joystick and DCC control. As well, geometric error compensation is included.

2.3. Motion Control Tuning

A key new feature of the CMM controller is a remote graphical interface for motion control tuning. The 100BaseTX Ethernet is connected from the controller to a remote computer that executes a special Microsoft VisualBASIC setup program. This program begins a back and forth motion on the selected CMM axis, and in real time the controller returns samples of the commanded position, actual position, and servo voltage. Samples are held in a First In First Out (FIFO) queue (Fig. 2(b)) and, to reduce communications overhead, are transmitted to the setup computer in groups of 5. For a 133 MHz Pentium, this task consumed less than 15 percent of the available processing time. The setup program plots the received samples as a strip chart (Fig. 3) [14], and the service engineer can instantly update the PID tuning parameters until the desired performance is obtained. Other capabilities of the setup program include CMM homing, digital readout and joystick operation, switch status information, and editing of geometric error compensation data.

2.4. Optical Probe Integration

A Hymarc Hyscan 45C [15] was used as the laser digitizer. It independently obtains linear scale coordinates using optoisolation electronics (Fig. 4). This situation is typical of new sensors in that the laser digitizer manufacturer and CMM manufacturer are two independent companies. As a rule, the CMM manufacturer geometric error compensation table is unavailable to the laser digitizer manufacturer. These digitizers are often used in less environmentally controlled surroundings, and hence temperature influence is significant.

To investigate the potential improvements that can be achieved by integrating the error compensation information, the CMM was error mapped for linear and squareness errors at 20, 25, and 30 degrees Celsius using a laser interferometer and conventional touch probed ball bar. The laser digitizer was then mounted on the CMM. A special ball bar was constructed by replacing the usual touch probed spheres with optically diffuse 76.25 mm diameter spheres, spaced approximately 404 mm apart. To emphasize the XY squareness correction, an error of 170 arc seconds was deliberately retained in the mechanical setup of the bridge. Plots of the uncompensated and compensated ball bar lengths for the 20 ASME B89.4.1-1997 locations ([16], Fig. 26) are shown in Fig. 5. The ball bar length dispersion was reduced by 82 percent (20 deg C), 79 percent (25 deg C), and 63 percent (30 deg C).

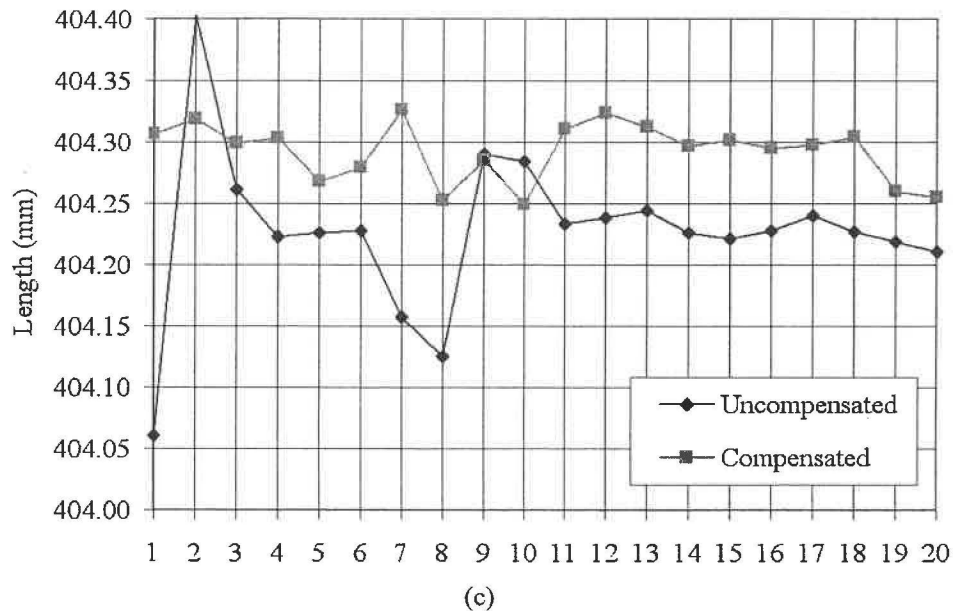
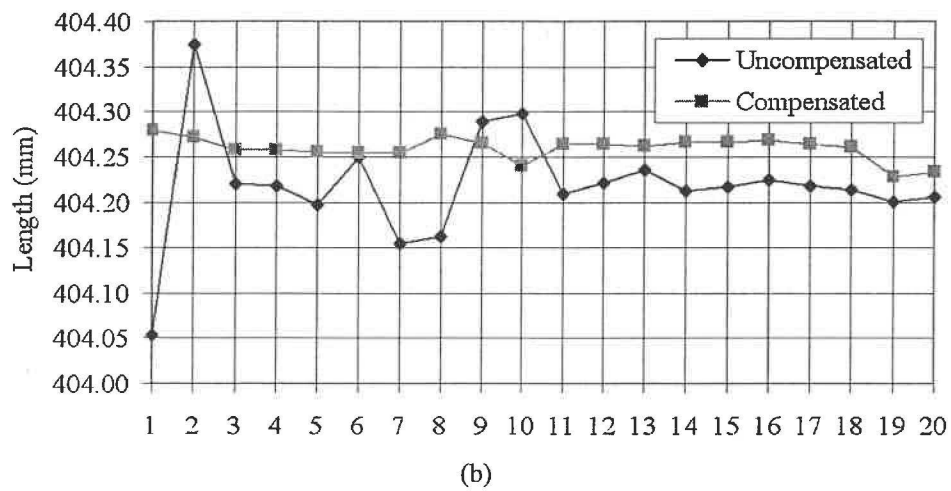
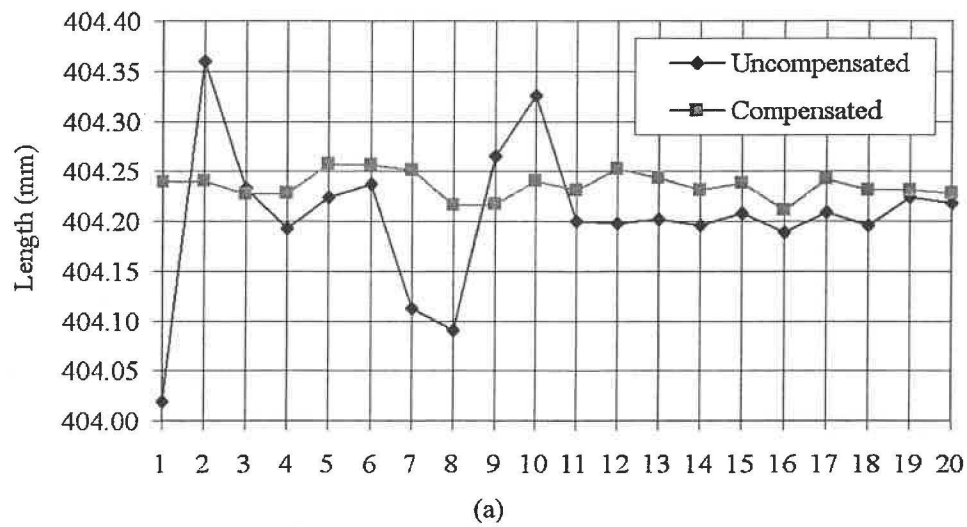


Fig. 5. Optical ball bar uncompensated and compensated lengths. Positions 1-20 correspond to [16], Fig. 26. (a) 20 deg C; (b) 25 deg C; (c) 30 deg C

2.5. Communication Standards

As new international communication standards are adopted, the control can be adapted without major revision. For example, I++ is supported by implementing a special TCP/IP bridge program on the metrology computer that converts I++ commands to/from the OTC5000 command language that the controller communicates with. This avoids the need to update the controller firmware. Interim support for OSIS can be implemented in a similar way.

3. Conclusions

This paper has described a new, embedded system style CMM controller. The unit uses a single Intel Pentium microprocessor for all functions including real-time motion control. The firmware is stored on flash disk, and is easily replaced using FTP. Setup, including real-time motion control tuning, is performed using 100BaseTX Ethernet, and a special GUI program that executes on a remote notebook computer. The controller is easily extended to support new analog touch and laser non-contact probes. Integration of CMM structure and laser digitizer geometric error compensation includes thermocouple based temperature compensation, and was evaluated using the ASME B89.4.1-1997 test with a special optically coated sphere ball bar. On average, a 75 percent reduction in ball bar length dispersion was attained.

Acknowledgements

The authors gratefully acknowledge receipt of research funding from the Canada Foundation for Innovation, Ontario Innovation Trust, Materials and Manufacturing Ontario, and Networks of Centres of Excellence-The Automobile of the 21st Century. The IOTA-P CMM was donated by BSB Machining (Stoney Creek, ON), and the GeoMeasure software from Mitutoyo America Corporation.

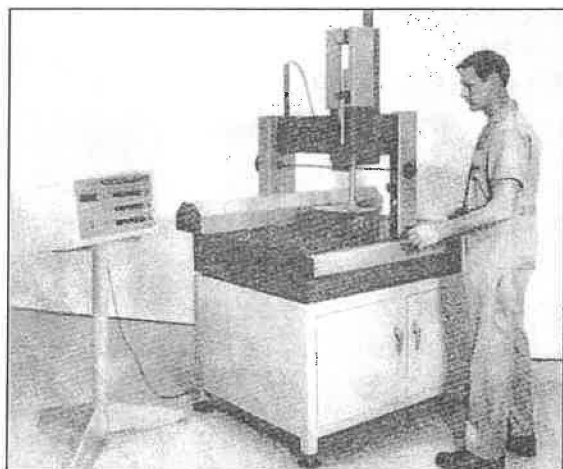
References

- [1] Bosch, J.A., Ed., *Coordinate Measuring Machines and Systems*, Marcel-Dekker, Inc., New York, NY, 1995.
- [2] Sartori, S. and Zhang, G.X., "Geometric Error Measurement and Compensation of Machines", *Annals of the CIRP*, 44/2, 599-609, 1995.
- [3] Consortium for Advanced Manufacturing – International (CAM-I), *Dimensional Measuring Interface Standard v4.0 Part I*, Bedford, TX.
- [4] Biedenbach, H.-M., Brunner, J., Gläsner, K., Moritz, G., Pfeifle, J., Resch, J., *I++ Dimensional Measuring Equipment Specification v1.3*, International Association of Coordinate Measuring Machines Manufacturers (ia.cmm) c/o Ernst & Young - ATAG Association Management Ltd, PO Box 8022 Zurich – Switzerland.
- [5] Boucky, O., *Optical Sensor Interface Standard*, International Association of Coordinate Measuring Machines Manufacturers (ia.cmm) c/o Ernst & Young - ATAG Association Management Ltd, PO Box 8022 Zurich – Switzerland.
- [6] Pritschow, G., Altintas, Y., Jovane, F., Koren, Y., Mitsuishi, M., Takata, S., van Brussel, H., Weck, M., and Yamazaki, K., "Open Controller Architecture – Past, Present and Future", *Annals of the CIRP*, 50/2, pp. 463-470, 2001.
- [7] Kramer, T., Procter, F.M., Rippey, W.G., and Scott, H., *The NIST DMIS Interpreter v2*, NISTIR 6252, National Institute of Standards and Technology, Gaithersburg, MD.
- [8] Renishaw plc, *UCC1 Installation Guide*, New Mills, Wotton-under-Edge, Gloucestershire UK.
- [9] Rippey, W.G., Michaloski, J.L., Herman, M., Szabo, S., DeWys, W., Frampton, N., Lau, H., Lee, E.S., and Rose, J., *NGIS SIM Specification*, NISTIR 6116, National Institute of Standards and Technology, Gaithersburg, MD.
- [10] Renishaw plc, *SP600 Analogue Scanning Probes*, New Mills, Wotton-under-Edge, Gloucestershire UK.
- [11] Servo To Go, Inc., *ISA Bus Servo I/O Card Model 2 Hardware Manual*, Indianapolis, IN.
- [12] VenturCom, Inc., *Phar Lap ETS Real-time Kernel*, Waltham, MA.
- [13] Omni-Tech Corporation, *OTC5000 Interface Specification Rev Q*, Fenton, MI.
- [14] IOComp Software, *Instrument Pack Pro*, Orlando, FL.
- [15] Hymarc 3D Vision Systems, *Hyscan 45C 3-D Laser Digitizer*, Nepean, ON.
- [16] American Society of Mechanical Engineers, *Methods for Performance Evaluation of Coordinate Measuring Machines*, ASME B89.4.1-1997, New York, NY.

RUSS SHELTON: FATHER OF THE CMM

Andrew J. Devitt
New Way Precision, Aston, PA

Russ Shelton is considered by many to be the father of the coordinate measuring machine. Certainly his work heavily influenced the structural materials, the design architecture, the types of bearings, and the probes used in the coordinate measuring machines. These notes hope to document just some of the contributions that Russ Shelton made in the measuring machine industry.



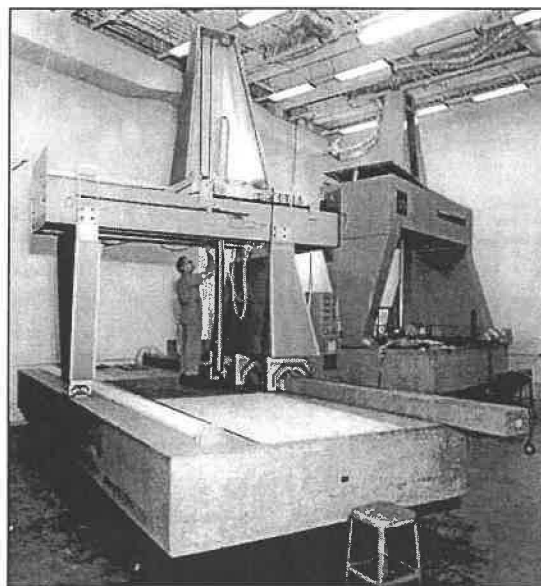
Russ Shelton with an early Check-Mate 1965

By 1965 Russ Shelton had already manufactured several coordinate measuring machines employing granite for structural components and air bearings for guidance. Prior to this almost all measuring machines had been based on machine tool design. Made from cast iron components with scraped or lapped oil lubricated ways, they were very expensive and required craftsmanship in their construction and care in their use. Russ used the stability and economics of granite and the technical advantages of air bearings combined with his own innovative ideas and machine architecture to found a new company called Shelton Metrology in 1965. In the promotion of his new metrology tools he needed to sell the idea of granite as a structural element. Everyone had granite surface plates but machine structures from granite were new.

At the same time Russ was developing and promoting the idea of porous air bearings. This

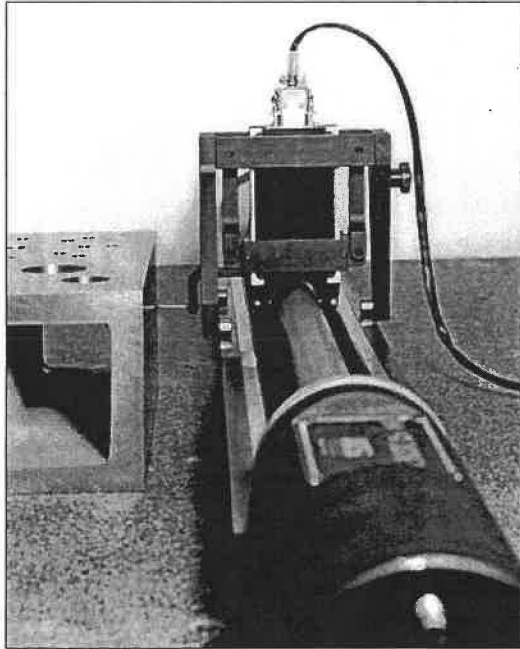
was a complete departure from conventional air bearings. The first porous bearings were made from sintered bronze. He learned the hard way that because the bronze was malleable, it was difficult to machine the same way each time and that contact with the guide way would change its flow characteristics. Many other porous materials were tried; stainless steel, nickel, and ceramic. After years of experimentation porous graphite was chosen as the best material for such use.

Russ's early CMMs employed many fine precision machine design principles; notice the widely space guide bearings and also the early use of friction drives. The double bridge design has been lost on most contemporary builders, this feature eliminates any roll force about the bridge and is an important consideration because cross bridge roll especially on long and or tall bridges is a large error source and difficult to compensate for.



First extremely large air bearing CMMs. Electro Motive (foreground) and Y12 (background)

Many Shelton Metrology machines are still in operation after 30 years and I have heard more than one service technician say these machines are superior with regard to reversal errors and uncorrected accuracy.



Veritas: uses Axis of Rotation
for straightness reference

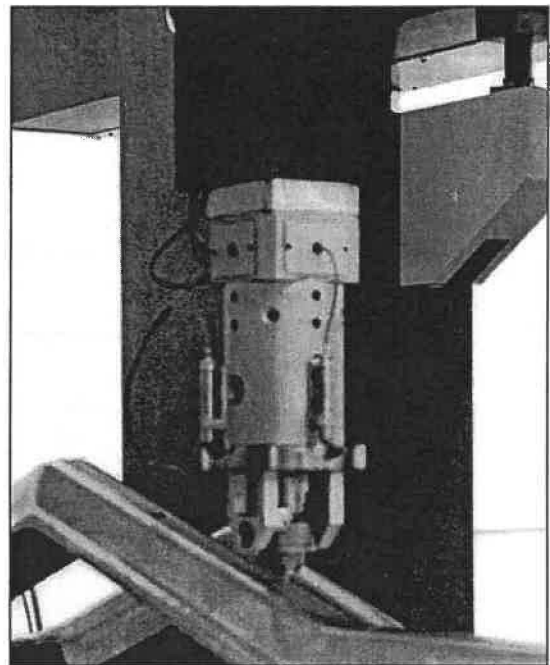
Russ received a Design News award for Veritas, deemed to be one of the 100 most significant inventions of 1971. The Veritas was a device for measuring straightness by spinning a shaft between two opposed spherical air bearings and then measuring both sides of the spinning shaft with differential probes. In this way he could divine out the axis of rotation and use it as a straightness reference. He would joke you could measure millionths of an inch by spinning a wooden 2 x 4. In all seriousness, by integrating the Veritas into his CMMs he could provide straightness-measuring resolution of one millionth of an inch, and accuracy of ten millionths over 56 inches. Thirty years later commercial CMMs are still not capable of matching these specifications.

Russ would resort to natural physical references when ever possible. For instance, to define a plane he would use pools of mercury connected by tubes and reference them with capacitive probes. By backing out the calculated

curvature of the earth he could establish a very accurate, inexpensive and flexible flat reference.

The first probes for CMMs were simply hard amounts of artifacts. Russ designed the first electronically triggered probe and it had a magnetic breakaway feature. His design allowed the operator to replace the probe without any need to recalibrate the machine probe relationship.

Russ then designed the first indexing touch trigger probe which was installed on one of his check-mate machines. That probe remained in use from 1971 until 1995 when it was replaced by an EMD scanning probe.



Early indexing trigger probe 1971

Russ was one of the first to build scanning probes for CMMs. He offered manual scanning probes in the mid 70s and CNC versions by the mid 80s. He was an early proponent of large amounts of data to more fully describe a part.

Acknowledgements:

Klaus Ulbrich, Electronic Measuring Devices, Inc. (973) 691-4755
Richard Davis, Davis Metrology (270) 443-7843
Stephen Eisenbies, Sandia National Laboratories

The Validation of CMM Task Specific Measurement Uncertainty Software

S. D. Phillips, B. Borchardt, A. J. Abackerli,[†] C. Shakarji, and D. Sawyer
National Institute of Standards and Technology, Gaithersburg, MD 20899

P. Murray and B. Rasnick
BWXT Y-12, L.L.C., Oak Ridge, TN 37831

K. D. Summerhays, J. M. Baldwin, R. P. Henke, and M. P. Henke
MetroSage L.L.C., Volcano, CA 95689

1. Introduction

Historically metrologists have attempted to purchase accurate coordinate measuring machines (CMMs) by specifying small values of standardized performance test results such as those defined by the ASME B89.4.1 or ISO 10360 standards. These standardized tests typically involve very simple measurands, such as point-to-point length, measured on highly idealized and geometrically simple artifacts such as gauge blocks, step gauges, and ball bars. While such tests are useful from a commercial transaction viewpoint, i.e., all manufacturers specify their CMM performance to the same tests, which allows easy comparisons between brands, the test results are usually only vaguely indicative of accuracy for the complex tasks that the metrologist performs on CMMs. Consequently, the evaluation of task specific CMM measurement uncertainty was either an outright guess, or a time intensive investigation involving measurements of calibrated artifacts geometrically similar to, and measured in a manner specific to, the task under consideration.

In the last several years, computer (Monte Carlo) techniques have arisen to assist in CMM task specific uncertainty evaluation. These simulation methods offer the potential advantage of highly detailed and advanced mathematical models of CMM error propagation that can be easily configured to the specific measurement task under consideration. Hence metrologists have a new and powerful tool that can answer such questions as:

- “Will the CMM I intend to purchase meet the accuracy requirements for my unique workpieces?”
- “What is the uncertainty of my current measurement results?”
- “If I change some aspect of my measurement (e.g. the thermal environment, the stylus configuration, or the point sampling strategy) what will be the consequence for the measurement uncertainty?”

The ability to simulate the details of the measurement task also implies significant complexity as each new task option multiplies the number of possible measurement scenarios. Consequently such simulation programs are often comprised of many megabytes of compiled computer code. Unfortunately, like all complex software, validation of the code is a nontrivial task. Indeed, even the (usually less complex) CMM software that actually performs and analyzes the measurements is only validated at a very elementary level. (Typically this involves testing the geometry fitting algorithms for mathematical correctness, but omits all the relational aspects (e.g. concentricity), datum reference frames, and material conditions (e.g. Maximum Material Condition)).

In this paper we discuss several methods of identifying weaknesses in CMM simulation software. In particular, we have the benefit that some of the authors are actually developing CMM task specific simulation software and we have listed some of the difficulties addressed during the development of that software project.

In principle, developing software testing procedures is much more straightforward if the inner workings of the simulation software are well understood. Some Monte Carlo methods use sophisticated first principle mathematical models to propagate CMM error sources. Two such methods are the “virtual CMM” [1] and “PUNDIT/CMM”[‡] [2] both of which use, for example, full rigid body parametric error models and kinematic equations to propagate these error sources forward into point coordinate errors and ultimately into corresponding errors of the parameters, e.g. diameter, of the fitting algorithms. Other systems use only random perturbations of the measurement points (which contain no information about correlated errors, e.g. CMM axis squareness) and calculate the corresponding errors of

[†] Permanent address: Universidade Metodista de Piracicaba – UNIMEP, Piracicaba-SP, Brasil, 123400-911

[‡] Disclaimer: The identification of any commercial product or trade name does not imply endorsement or recommendation by the National Institute of Standards and Technology or by BWXT Y12.

the parameters of the fitting algorithms. Still other systems use empirical models. Unfortunately, since the source code is unavailable, any of these systems can be examined only as a "black box" where a specified set of input values results in an observed output value, a calculated expanded uncertainty.

2. Factors for Consideration in Testing

Blunders: It has often been said that the largest source of measurement error is misinterpretation of a Y14.5 drawing. While such problems clearly exist, mistakes of this source are considered by the GUM (ISO, "Guide to the Expression of Uncertainty in Measurement," Switzerland, 1993, corrected and reprinted 1995) as "blunders" and are not to be included in the measurement uncertainty statement (GUM 3.4.7). To the list of blunders we include improperly setting up an uncertainty simulation run and hence getting inappropriate uncertainties.

Uncertainty of the Measurand: The GUM identifies that a poorly specified measurand is a legitimate source of measurement uncertainty as it gives rise to multiple "true values" all of which can be assigned as the "value of the measurand". It is the metrologist's obligation to consider this issue and quantify it; hence we do not consider this source of uncertainty (which is also frequently overlooked in traditional uncertainty analysis) in our investigation.

Simulation Fidelity: We define the "simulation fidelity" as the ability of the simulation software to faithfully represent the details of a real measurement in the simulation; how accurately the software models these details is a separate issue addressed elsewhere. All real measurements have an almost infinite list of influence quantities that affect the measurement result and all simulation software has a finite list of uncertainty sources that can be included in the calculated uncertainty. Poor fidelity does not allow the details of the measurement to be specified in the simulation software, and hence the simulation provides an uncertainty statement for a measurement scenario different from the real measurement. Good fidelity simply means that details of the measurement can be represented in the simulation; whether the software considers these details correctly is addressed elsewhere in this paper. Uncertainty contributors can be considered either as intrinsic to the measurement system (i.e. sold with the CMM) or extrinsic. A few examples of influence quantities include:

Extrinsic factors: CMM operator effects, especially workpiece fixturing variation; workpiece form error and how it interacts with the probing point sampling strategy; thermal properties and conditions of the workpiece; workpiece contamination (dirt or coolant...)

Intrinsic factors: Multiple styli (either fixed star probe or an articulated stylus); scanning probes; rotary tables; CMM dynamic effects (changes in acceleration and velocity values)

In real measurements there will always be some factors that are not represented in the simulation, i.e. the simulation fidelity will not be perfect. This has two consequences: (1) in the evaluation of measurement uncertainty the CMM user is obligated to account for uncertainty sources that are not included in the simulation software; (2) in testing simulation software great care must be given to minimizing the influence quantities that are not accounted for in the simulation software; hence testing measurements must be constructed such that they can be simulated with good fidelity and the calculated uncertainty can be compared to the observed measurement errors.

Simplified, Incomplete, or Incorrect Mathematical Modeling: Assuming that the simulation software allows the inclusion of a particular influence quantity, e.g. describing the form error on a workpiece, or allowing the use of multiple styli, some sort of mathematical model must be invoked to calculate the errors due to this influence. These models can range from complex first principle derived models, to very simple approximations, to just plain wrong models that do not describe the behavior of the influence quantity.

Input Parameters: All models require some form of input to quantify the influence quantities. These input values may be extracted from actual measurement data collected on the CMM under simulation or may be user supplied. These input values describe such things as the type of probe, the magnitude of the probing error, the type of CMM, the magnitude of the CMM structural errors, the type of workpiece form error and its magnitude, etc. Even a very detailed and accurate model will yield nonsense if the input parameters are incorrect.

Coding Errors: In all large complex software systems, coding errors will be present. These can range from a simple incorrect logic statement to more subtle effects such as failing to clear registers or unanticipated interactions when function or object calls occur in different sequential order.

3. Methods of Testing

The procedures for testing CMM measurement uncertainty simulation software are still in an embryonic stage. Indeed, even testing the reliability of uncertainty statements produced by conventional means (e.g. using sensitivity coefficients as described in the GUM) is still controversial and under development. The GUM clearly recognizes the distinction between error and uncertainty, and in particular, points out that a measurement result might (unknowingly) have little error yet be assigned a relatively large uncertainty. This would correctly describe the metrologist's uncertainty about the result. Consequently an uncertainty statement cannot be invalidated because it is large relative to the measurement errors. However, an uncertainty statement can be invalidated if a significant fraction of errors lie outside the uncertainty interval, since the GUM interpretation of expanded uncertainty is that roughly 95 % of the errors (unless otherwise stated by the metrologist) will lie within the uncertainty interval. It is this criterion that we use to test simulation software. We believe that vast overestimation of measurement uncertainty will be eliminated in the commercial marketplace as uncertainty statements are used either to indicate the quality of a measurement result (e.g. calibration laboratories) or to establish gauging guardbands on workpiece tolerances to insure product reliability; in either case overestimation of measurement uncertainty will have large negative economic consequences.

The ISO TC213/WG10 working group is developing a document (15530-4) addressing CMM measurement uncertainty via computer simulation. One aspect of that document is a disclosure of what measurements and influence quantities can be addressed by the simulation software, i.e. a description of the simulation fidelity. Also in the document, several general approaches are discussed: (1) comparison of errors found by the actual measurement of calibrated artifacts to the uncertainties calculated by simulation; (2) comparison of special case "reference values" uncertainties to the uncertainties calculated by simulation; and (3) comparison of "computer-aided verification and evaluation" (CVE) uncertainties to the uncertainties calculated by simulation.

Physical Measurements: The most direct method of examining the validity of an uncertainty statement produced by computer simulation is by physical measurements of calibrated artifacts. Ideally, the physical measurements will be performed in a manner that allows good simulation fidelity so that the calculated uncertainty statement can be directly interpreted as including at least 95 % of the measurement errors.

We have conducted several measurements of this type as shown in Figure 1. The figure shows both the calculated computer simulated uncertainty and the corresponding measurement error of a 150 mm diameter XX grade ring gauge positioned in multiple locations in the CMM workzone. The ring was sampled with 24 equally spaced points and the diameter and circularity were measured. The CMM was a moving bridge style with a workzone (X, Y, Z) of 460 mm, 460 mm, and 385 mm. The CMM was equipped with an articulated head and the probe used was a touch trigger type. We performed the measurements with the CMM error compensation (which corrects for geometrical errors in the CMM structure) both OFF and ON, giving in effect two different CMMs. Table 1 gives the performance parameters of the CMM for both cases. Maximum Permissible Error (MPE) is defined by ISO Standard 10360-5. Figure 1 (a) shows the diameter and circularity errors and simulated uncertainties for the ring gauge. The ring orientation follows the B axis of the articulation system to keep the ring plane perpendicular to the probe axis. Two measurements are shown at B = 0; for one the ring is in the XY plane and for the other the probe is pointed along the -Y axis of the CMM and the ring is in the XZ plane. The other orientations are taken every 45 degrees, with the ring and probe direction rotating about the CMM Z axis, e.g. B = 90 with the ring in the YZ plane. Figure 1 (b) displays the same type of data for the ring tilted 30 degrees with respect to the table and indexed every 45 degrees about the CMM Z axis; hence this includes positions with a diameter of the ring along the four CMM body diagonals. Figure 1 (c) and (d) show the corresponding information for the CMM with the compensation turned OFF.

Table 1

CMM Performance (B89.4.1)	Compensated	Non-compensated
X linear accuracy	5.5 μm	11 μm
Y linear accuracy	6.5 μm	12 μm
Z linear accuracy	3 μm	88 μm
Volumetric performance	13.5 μm	188 μm
Offset probe volumetric performance	50 $\mu\text{m/m}$	76 $\mu\text{m/m}$
Repeatability	0.8 μm	0.8 μm
Probe performance	7 μm	7 μm
MPE _{AF} , MPE _{AS} , MPE _{AL} (ISO)	10 μm , 2 μm , 3.8 μm	16.6 μm , 3.1 μm , 5 μm

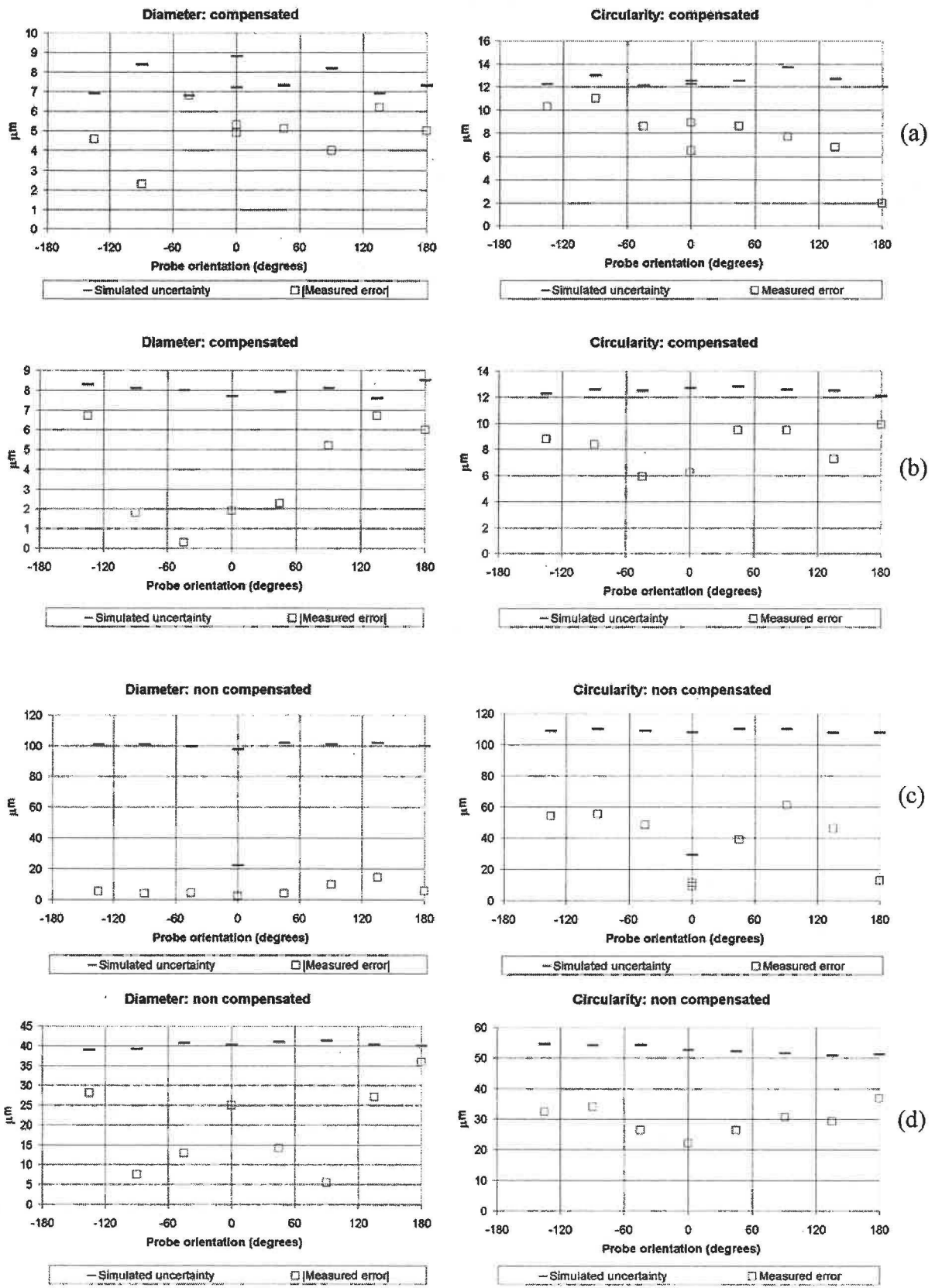


Figure 1

Figure 2 displays additional physical testing using a high accuracy CMM with an analog probe with performance values given in Table 2. In this case the artifact was a 300 mm diameter disc measured for diameter and circularity similarly to the measurements of Figure 1, but with 360 points. The styli used in these measurements were “L” shaped with each leg typically 80 mm. Due to some simulation fidelity issues with this version of the software we were forced to use styli of only approximate dimensions; however, we do not believe this significantly changed the calculated measurement uncertainty.

Table 2	
CMM Performance (B89.4.1)	Values
X linear accuracy	1.2 μm
Y linear accuracy	1.4 μm
Z linear accuracy	2.2 μm
Volumetric performance	3.9 μm
Offset probe performance	6.7 $\mu\text{m/m}$
Repeatability	0.34 μm
Probe ISO 10360-2 (25 points)	0.82, 1.68, 1.82 μm

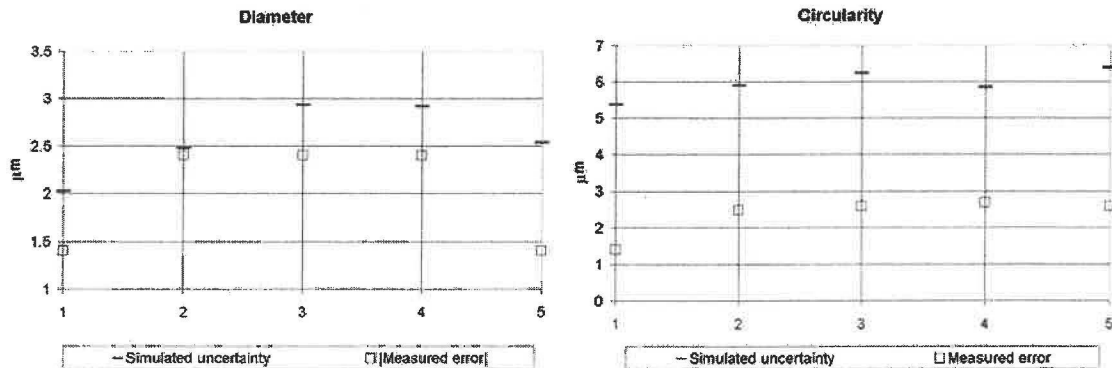


Figure 2

Reference Values: A powerful technique to detect problems in measurement uncertainty software involves the use of reference values. A reference value is a special case result that has a known value. This value can be obtained through a variety of means, including using other verified software known to produce a mathematically correct answer under specified conditions. Often the “reference value” can be obtained through some type of invariant quantity. Our use of reference values in this investigation is rather happenstance, however, we are in the process of a more systematic approach to this method. We describe below some anecdotal cases where reference values have proved useful.

Invariance: The simulation software under consideration can be configured in a variety of ways including deactivating entire classes of uncertainty sources. Thus it was possible to examine a geometrically perfect CMM and introduce as the sole uncertainty source only probing errors. Hence it can be expected that the uncertainty of some simulated measurement, e.g. the diameter of a ring gauge, should not depend on the particular location in the CMM workzone, provided the same number of probing points are measured with the same probe approach direction, etc. That is, while there may be some statistical variation dependent on the number of simulation cycles, in the limit of a large number of cycles this value should be invariant under changes in workpiece location. The simulation software under consideration has the fidelity to locate the workpiece at any location in the CMM workzone. It was observed that after a large number of workpiece relocations, the uncertainty of the simulated measurement was increasing. Eventually this was tracked down to the manner in which the relocations were calculated, as a series of transformation matrices from the previous position. Hence after dozens of workpiece relocations a very long sequence of matrices was being multiplied, allowing minor round off errors to get magnified. The solution was obvious, namely a workpiece relocation was always transformed from a reference position, not the previous position, hence involving only one transformation matrix for each location.

Known values: Zero is a powerful reference value. When all inputs are set to zero, a perfect measurement is being considered, and so the simulation should yield zero measurement uncertainty. While most of the various modules satisfied this result, we have found one probe module that yields small (submicrometer) expanded uncertainties indicating a problem that is currently under investigation.

Other known results can be used to test the simulation software. For example, a workpiece temperature can be set to 21 °C with zero uncertainty and a thermal expansion coefficient set to 10^{-5} / °C with zero uncertainty, hence the

result for a one meter feature of size measured without thermal compensation should yield a systematic error of +10 μm and the simulation software should produce this result, and for our test software it did so.

If well-tested reference software is available it can be used to produce known values. For example, NIST has an algorithm testing software package used to check least squares fitting algorithm for the mathematically correct result. We used this software to produce the diameter of a circle that was perturbed by a systematic form error (e.g. three lobes) of specified amplitude. Using the reference software, a large set of results was produced for different phase combinations of the sampling points and the form error. Twice the standard deviation of these results can be compared to the CMM simulation of a similar form error and sampling strategy. We noticed that the reference software and the CMM simulation software were converging to different uncertainty values for the circle diameter. Upon further investigation the problem was discovered to be a coding error in the simulation software that caused N equally spaced points on a circle to have a point both at 0 degrees and 360 degrees, i.e. one location on the circle had two superimposed points. A revised version of the simulation software corrected the problem leading to equivalence between the reference and CMM simulation uncertainties.

Sometimes specific uncertainty results can be determined analytically. For example, the measurement of a circle with three points each separated by an angle θ is known to produce an uncertainty in the radius given by the equation below, where σ is the standard deviation of a Gaussian distribution of radial perturbations [3]. In these analytic cases it is straightforward to check the simulation results.

$$u^2(\text{radius}) = \frac{1 + 2\cos^2\theta}{2(1 - \cos\theta)^2} \sigma^2$$

Computer-aided Verification and Evaluation (CVE)

This powerful testing method allows for great control in determining the ability of the software under test to reflect certain isolated influence factors in its reported uncertainty. The details of the method are given in [4], but we outline the basic concepts here. In physical testing, several measurements are made and compared with calibrated values. The CVE approach is similar, but measurements are made by a CMM that exists—not physically—but rather as a model within a computer program. Given a CMM model, a program can easily simulate thousands of measurement tasks with exactly known measurement errors. The same CMM model can be used to obtain the needed input quantities to the uncertainty evaluating software. The known measurement errors can be compared with the uncertainty reported by the software under test to find the percentage that lie within the stated uncertainty. One can then repeat this test over many modeled CMMs—a prohibitive task if relying solely on physical testing. This CVE technique works with other influence factors (besides the CMM itself) provided realistic models are known. While we did not investigate CVE techniques in this paper, they represent a generalization of the reference value method and will be presented in a future publication.

3 Conclusions

Our preliminary investigation of validating CMM measurement uncertainty statement produced by computer simulation produced a variety of results. All of the measurement errors found in the physical measurements were well inside their corresponding uncertainty intervals. The physical measurements are only able to test error sources that are actually present during the measurement. For example, if our CMM had no XZ or YZ axis squareness error then we would be unable to determine if the simulation software would correctly handle this class of CMM errors. Since in general the details of the CMM errors are unknown, physical testing on several CMMs is warranted in order to get a good representation of all potential CMM error sources and exercise the simulation software over this population of error sources. To the extent that the uncertainty appears to be overestimated in some cases of the physical measurements (Figures 1 and 2), this may indicate that further refinements in the simulation software may be useful.

The physical measurement results were unable to detect the problems in the simulation software involving the part placement transformation matrices, the switching probe error, or the redundant point sampling strategy error, as these effects were typically submicrometer and not discernable in the results. The reference value testing can catch these errors relatively quickly in cases where one knows what reference value to employ and corresponding measurement to simulate. This suggests that a well-documented list of reference value tests might be a useful tool to employ before starting the more expensive aspect of real physical measurements of calibrated parts.

1. <http://www.ptb.de/en/org/5/53/532/vcmm.htm>
2. www.metrosage.com
3. S.D. Phillips, et. al., Precision Engineering 22: 87-97, 1998
4. S.D. Phillips, Proceedings ASPE 1999 Annual Meeting 525-528

Manufacturing Signatures and CMM Sampling Strategies

Giovanni Moroni**, Wilma Polini*, Marco Rasella**

**Dipartimento di Meccanica, Politecnico di Milano,
piazzale Leonardo da Vinci 32, Milano, 20133, Italy

*Dipartimento di Ingegneria Industriale, Università di Cassino,
via G. di Biasio 43, Cassino, 03043, Italy

1. Introduction

The “task specific uncertainty” in coordinate metrology is the measurement uncertainty that results, computed according to the ISO Guide to the Expression of Uncertainty in Measurement (GUM), when a specific feature is measured using a specific inspection plan. Measurements commonly are of size, form, or position and involve features dimensioned and toleranced in accordance to international and national standards. The use of coordinate measuring machines (CMMs) and other discrete point sampling devices in coordinate metrology raises questions regarding the proper interpretation of data. The methods divergence problem in coordinate metrology is a well-known phenomenon when dealing with discrete measurement data. The problem may be divided into two categories:

- different data analysis algorithms give different inspection results when using the same set of measurement data;
- different sampling schemes produce different inspection results for the same part, even when the same data analysis algorithm is used.

In addition to these fundamental issues, economic considerations argue for more efficient and reliable measurements. This has led to a search for sampling strategies and data analysis methods that maximize the information available from discrete points samples of limited size.

In this paper we tackle the problem of the choice of an appropriate sampling strategy starting from the consideration that the characteristics of a surface are directly attributable to the manufacturing methods. In fact, different type of error sources in the manufacturing system leave different signatures on the part, and the geometric errors on the part are the results of the combined effect of all these error sources. However, even if these manufacturing signatures play an important role in the task specific uncertainty estimation, they typically are not taken into account. The paper will be particularly focused on form error assessment.

In previous works the machining process analysis has been used to describe the error that affects the estimate of a circular substitute geometry in the frequency domain [1,2]. In this situation the radius of the fitted substitute geometry may be approximated by the amplitude of the harmonic of order zero, while the position of the center can be approximated by the value of the first harmonic (absolute value and phases) [3]. A further attempt to use the profile knowledge, admitted by means of a pre-sampling, to locate the sampling points is shown in [4].

This work deals with the effect of the machine-tool errors on the profiles of machined parts. A cutting profile model is derived from a machining error model [5]. It allows to foresee the fingerprint left by turning process on the machined part, i.e. every process

generates surfaces with similar morphology. This model is used to choose the number of measurement points on the machined profile in order to evaluate its roundness error.

Once sampled the machined profile, the roundness error is evaluated by means of an innovative approach based on the reconstruction of the machined profile in the frequency domain. The proposed method has been tested for different numbers of measurement points. The innovative approach has been compared with the widest used techniques that consider unknown the manufacturing process, i.e. least square and minimum zone methods [6], and with the standards. The least square method associates a substitute feature, i.e. an ideal circle, to the measurement points, and calculates the maximum peak-to-valley distance of the measurement points from the substitute feature. In the literature many goal functions exist to estimate the substitute feature, such as the sum of the square deviations [7], the sum of the square normal deviations [7,8], the sum of the absolute deviations [9,10] and the average deviation [9]. The minimum zone method looks for the couple of concentric circles at minimum distance that includes the whole set of measurement points. The literature present different mathematical [11] or geometry-based techniques [12] to estimate the couple of circles.

The trend of the uncertainty due to the measurement strategy, i.e. both to the sampled points and to the elaboration technique, has been drawn with the increase of the number of the sampled data points. It has been used to evaluate the most efficient algorithm in roundness evaluation of turned parts. The same method may be used for parts machined by means of different technologies, such as grinding, boring and so on.

2. Roundness form error evaluation

A machined circular profile may be seen as a periodic wave with period 2π and may be completely described by its Fourier representation:

$$r(\vartheta) = r(\vartheta + 2\pi) = a_0 + \sum_{i=1}^{\infty} a_i \cos(i\vartheta) + \sum_{i=1}^{\infty} b_i \sin(i\vartheta) = a_0 + \sum_{i=1}^{\infty} A_i \cos(i\vartheta - \varphi_i) \quad (1)$$

where $A_i \cos(i\vartheta - \varphi_i)$ is the i^{th} harmonic component of $r(\vartheta)$. The amplitude of this component is A_i , while its phase displacement, measured in radians, is φ_i .

When equation (1) is applied to machined circular profiles, it can be observed that the amplitude of the harmonics tends to decrease as frequency increases, even if the reduction is not monotonic. This is due to the physics of the process that generates the circular surface [13] and to the finite value of the probe radius which acts as a physical low-pass filter. Hence, over a certain harmonic N it can be supposed that $a_i = b_i = 0$ for $i > N$ and the machined profile can be described with good approximation by the following equation:

$$r(\vartheta) = a_0 + \sum_{i=1}^N a_i \cos(i\vartheta) + \sum_{i=1}^N b_i \sin(i\vartheta) = a_0 + \sum_{i=1}^N A_i \cos(i\vartheta - \varphi_i) \quad (2)$$

The proposed approach evaluates the coefficients a_i, b_i ($i = 1 \dots N$) of equation (2) by a finite number n of sampled points $r_k = r(\vartheta_k)$ through the well known relationships:

$$\hat{a}_0 = \frac{1}{n} \cdot \sum_{k=1}^n r_k \quad (3)$$

$$\hat{b}_0 = 0 \quad (4)$$

$$\hat{a}_i = \frac{2}{n} \cdot \sum_{k=1}^n r_k \cos(i\vartheta_k) \quad (5)$$

$$\hat{b}_i = \frac{2}{n} \cdot \sum_{k=1}^n r_k \sin(i\vartheta_k) \quad (6)$$

for $i = 1..N$.

The circular profile is estimated by means of the rebuilt harmonic spectra:

$$\hat{r}(\vartheta) = \hat{a}_0 + \sum_{i=1}^N \hat{a}_i \cos(i\vartheta) + \sum_{i=1}^N \hat{b}_i \sin(i\vartheta) \quad (7)$$

whereas the contribution of every single harmonic may be expressed using the following notation:

$$A_i = \sqrt{a_i^2 + b_i^2} \quad (8)$$

$$\hat{\varphi}_i = \arctan\left(\frac{\hat{b}_i}{\hat{a}_i}\right) \quad (9)$$

It is well known [3] that the radius of the fitted substitute geometry, obtained using the least squares method (LSM), may be approximated by the amplitude of the harmonic of order zero and that the position of the centre can be approximated by the value of the first harmonic (absolute value and phase):

$$a_0 = \hat{r}_{\text{LSM}} \quad (10)$$

$$a_1 \cos(\varphi_1) + b_1 \sin(\varphi_1) = \sqrt{a_1^2 + b_1^2} = e \quad (11)$$

$$\varphi_1 = v \quad (12)$$

where $\hat{r}_{\text{LSM}}$, e and v are the best estimate of the radius and of the position of the centre, in polar coordinates, with respect to the nominal centre of the nominal circumference in LSM. Therefore, the form error depends on the harmonics of order higher than one, i.e. from 2 to N . Applying the LSM, it may be calculated by using the remaining $N-2$ harmonics:

$$LSRoundness = \text{Max}\left(\sum_{i=2}^N a_i \cos(i\vartheta) + \sum_{i=2}^N b_i \sin(i\vartheta)\right) - \text{Min}\left(\sum_{i=2}^N a_i \cos(i\vartheta) + \sum_{i=2}^N b_i \sin(i\vartheta)\right) \quad (13)$$

Equation (13) may be applied, once known the spectrum of the machined profile. This spectrum is the fingerprint left by each machining process on the machined part. The proposed method to evaluate the roundness starts from the information taken by the machining process of the part. The number of harmonics constituting the spectrum is enough to implement the method.

The number of measurement points to evaluate equation (13) may be determined by means of the well known sampling theorem that is the basis of much of the modern signal-processing technology. The sampling theorem states that it is possible to completely describe a signal with N harmonics only if the sampling frequency is higher than or equal to $2N$. If the signal is sampled at a lower frequency, the phenomenon of aliasing takes place. Therefore, if a circular profile can be described by N harmonics (as supposed in equation (2)), the number of sampled point n should be higher than $2N$. Estimated profile (7) obtained with $n > 2N$ is identical and is the best representation of the real profile. When the number of sampling points is less than $2N$, the problem of aliasing occurs and the sampled spectrum

differs from the real one. In fact, all the harmonics $i > n/2$ of real spectrum are spuriously reflected inside range $[0, n/2]$ of the sampled spectrum.

However, the standards require to evaluate the form error through the minimum zone method, that means to look for the couple of concentric circles at minimum distance that includes the whole set of measurement points. Therefore, starting from the $2N$ points it is possible to reconstruct the machined profile and, then, use this profile to evaluate the minimum zone, reducing the uncertainty.

3. Application example to lathe machining

The proposed approach has been applied to a longitudinal turning operation whose data have been found in the literature [5]. Different specimens of a cylindrical steel bar of about 25.4 mm diameter and 50.8 mm length have been machined. The obtained bar section profiles has been measured by means of a rotondimeter and statistically described in the frequency domain by means of 50 harmonics.

The actual profile of the machined bar, in the frequency domain, has been generated by considering the statistical distributions of the amplitudes and the phases of the 50 harmonics shown in [5]:

$$r(\vartheta) = 25400 + \sum_{i=1}^{50} A_i \cos(i\vartheta - \varphi_i) \quad (14)$$

where A_i and φ_i follow a beta and a uniform distributions respectively:

$$A_i \sim B(\alpha_i, \beta_i) \quad (15)$$

$$\varphi_i \approx U(0, 2\pi) \quad (16)$$

for each i from 1 to 50 and $r(\vartheta)$ is expressed in micron. In particular 6 actual profiles of the machined bar have been generated. The first considers the average value of the distributions as amplitude of each harmonic. The further 5 cases have been simulated by randomly extracting the amplitude and the phase values of each harmonic.

The roundness error ε of the actual profile has been evaluated by sampling 10800 measuring points (i.e. 30 points every degree) on the profile and applying the minimum zone method.

Two different sampling strategy have been proved and compared. The first uses a number of measuring points equal to twice the number of harmonics (51 harmonics from 0 to 50); the second follows the standard ISO 12181 that states to measure 7 points for each undulation per revolution (UPR). The 102 and 360 points have been uniformly sampled along the generated circular profile. 10 replications have been carried out for each of the two sets of measuring points by randomly choosing the starting point. Therefore, we have generated 120 sets of measuring points to evaluate the roundness of the machined profile.

The coefficients of equation (14) have been estimated by means of (3)-(6) formulas and, then, the roundness value has been evaluated by using the reconstructed profile. The reconstructed profile was sampled by 2160 points and the minimum zone methods applied. The obtained results have been compared with those obtained applying the least square and minimum zone techniques directly to the samples of 102 and 360 points. We used Zeiss Calypso® software as reference software.

4. Results discussion

The percentage difference between the roundness estimate given by applying the proposed approach to each of the 10 sets of 102 measuring points and the actual value of roundness, i.e. the roundness value obtained by applying the proposed approach to the set of 10800 measuring points, has been calculated. The same difference has been evaluated, once applied to the same sets of measuring points the least squares and the minimum zone methods. We have obtained 6 distributions of percentage estimate error for each of the three applied techniques (proposed, least squares and minimum zone approaches). All the 18 distributions follow a normal probability distribution whose mean and standard deviation are shown in Table 1. The mean and the standard deviation are respectively the bias and the natural dispersion of the estimate with respect to the actual value. We can observe that the proposed method gives values of natural dispersion of the percentage error very lower than those due to both least squares and minimum zone. Moreover, the bias ranges between -3% and $+3\%$ for the proposed method, between -0.5% and 7% for least squares and between -5% and -11.4% for minimum zone.

Case study	Least squares		Minimum zone		New approach	
	μ	σ	μ	σ	μ	σ
1	4.08	5.65	-8.84	6.19	2.62	1.03
2	-0.49	6.81	-8.49	5.85	1.92	1.18
3	7.23	3.1	-8.58	2.41	-1.09	1.27
4	1.62	8.47	-11.16	4.66	-2.86	1.14
5	0.69	5.14	-11.36	6.11	1.37	0.80
6	-0.52	4.76	-4.87	5.23	0.83	0.77

Table 1. Mean and standard deviations of the distributions related to 102 points' sets

Then, it has been evaluated how the percentage estimate error improve by increasing measuring points for both the least squares and the minimum zone. The same analysis has not considered needed for the proposed approach, since the results obtained for 102 points are largely satisfactory. The 12 distributions follow a normal probability distribution, whose means and standard deviation are shown in Table 2. In particular the percentage estimate error mean and standard deviation due to least squares method range between 4% and 15% and between 1.3% and 2.4% , while those of minimum zone vary between -3.2% and 1% and between 0.9% and 2% . The least squares gives values of bias that are very higher than those of the proposed approach for each of the six considered profiles. The minimum zone achieves bias values similar to those of the proposed approach, but higher dispersion values.

Case study	Least squares		Minimum zone	
	μ	σ	μ	σ
1	13.99	1.84	0.28	1.3
2	9.95	2.36	0.94	1.49
3	14.99	1.28	-1.66	0.89
4	12.15	1.92	-3.23	1.22
5	11.76	1.84	0.86	1.61
6	4.20	2.13	-0.3	2.03

Table 2. Mean and standard deviations of the distributions related to 360 points' sets

5. Conclusions

The present paper draws the trend of uncertainty due to the measurement strategy, i.e. both to the sampled points and to the elaboration technique, with the increase of the number of the sampled data points. Both the bias and the natural dispersion of the estimate with respect to the actual value of roundness have been considered. The uncertainty trend has been used to evaluate the most efficient algorithm in roundness evaluation of turned parts. The same method may be used for parts machined by means of different technologies, such as grinding, boring and so on. This is matter of further study.

Acknowledgements

This work was carried out with the funding of the Italian M.I.U.R. (Ministry of Italian University and Research) and CNR (National Research Council of Italy).

References

- [1] Capello E., Semeraro Q., 2001, The harmonic fitting method for the assessment of the substitute geometry estimate error. Part I: 2D and 3D theory, *International Journal of Machine Tools & Manufacture*, vol. 41, 1071-1102.
- [2] Capello E., Semeraro Q., 2001, The harmonic fitting method for the assessment of the substitute geometry estimate error. Part II: statistical approach, machining process analysis and inspection plan optimization, *International Journal of Machine Tools & Manufacture*, vol. 41, 1103-1129.
- [3] Capello E., Semeraro Q., 1999, The effect of sampling in circular substitute geometries evaluation, *International Journal of Machine Tools & Manufacture*, vol. 39, 55-85.
- [4] Rossi A., 2001, A form deviation-based method for CMM sampling optimisation in assessment of roundness, *Journal of Engineering Manufacture*, vol. 215(11), pp. 1505-1518.
- [5] Cho N., Tu J., 2001, Roundness modelling of machined parts for tolerance analysis, *Precision Engineering*, vol. 25, pp. 35-47.
- [6] Feng S.C., Hoop T.H. 1991, A review of current geometric tolerancing theories and inspection data analysis algorithms, *NIST, Technical Report # 4509*.
- [7] Murthy, T.S.R., Abdin, S.Z., 1980, Minimum Zone Evaluation of Surfaces, *International Journal of Machine Tool Design Research*, vol. 20, pp. 123-136.
- [8] Shunmugam M.S., 1986, On Assessment of Geometry Errors, *Int. J. Production Research*, vol. 24 (2), pp. 413-425.
- [9] Shunmugam M.S., 1987, New approach for evaluating form errors of engineering surfaces, *Computer Aided Design*, vol. 17(7), pp. 368-374.
- [10] Wang Y., 1992, Application of Optimisation Techniques to Minimum Zone Evaluation of Form Tolerances, In: *Quality Assurance Through Integration of Manufacturing Processes and Systems*, A.R. Thangaraj (Ed.), ASME Press, vol. 56, pp. 15-28.
- [11] Carr K., Ferreira P., 1995, Verification of form tolerances. Part II: Cylindricity and straightness of a median line, *Precision Engineering*, vol. 17, 144-156.
- [12] Roy U., Zhang X., 1992, Establishment of a pair of concentric circles with the minimum radial separation for assessing roundness error, *Computer Aided Design*, vol. 24(3), pp. 161-168.
- [13] Damir M.N.H., 1979, Appropriate harmonic models for roundness profiles, *Wear*, vol. 57, pp. 217-225.

Calibrating and Testing CMMs in a World of Uncertainty and Accreditation

James G. Salsbury

Mitutoyo America Corporation, 945 Corporate Boulevard, Aurora, IL 60504

1 Introduction

Over the past five years, coordinate measuring machines, and the entire metrology industry, have been subject to increasing mandates for quantitative uncertainty estimates [1] and ISO/IEC 17025 accreditation [2] of calibration, test, and inspection services [3]. The philosophy behind these new requirements may not always be in-line with the philosophy behind the national and international standards for performance evaluation of CMMs [4,5]. Though much research has been done in the area of task specific uncertainty of CMM measurements, the uncertainty of the process to calibrate and verify the performance of a CMM has not received significant attention. The problem is much more complex than most may believe, and industry is currently struggling with what it means to calibrate and/or test a CMM and how to properly estimate the uncertainty of either process. The purpose of this paper is to address these critical issues.

In addition, the latest ISO standard on CMM performance, the revised ISO 10360-2:2001 [4], is just beginning to be used in industry. This standard, for the first time, requires that uncertainty be considered in the decision rule, following ISO 14253-1 [6], to verify the CMM meets specification or not. The result is competition in the area of uncertainty, which requires common practices to be followed or comparisons will have no value. In this paper, we claim that these common practices do not exist today and there is concern that the key purpose of the standards – allowing customers to make fair comparisons between machines – is being lost.

2 The New ISO 10360-2:2001

In the past three years, the entire suite of ISO 10360 standards for evaluating the performance of CMMs has gone through some significant changes. There now exists different standards for various aspects of CMMs, such as scanning and multiple tip use [4, 7-11], but the most important part of that series is still ISO 10360-2, which tests the overall volumetric performance of the CMM. The ISO 10360-2 standard was first released in 1994 and has quickly become the preferred standard worldwide. This standard is also widely used in the U.S. even though it is not the American standard. The new 2001 version has only introduced one change, but that change is subtle yet critically important. The standard now requires that all decisions regarding conformance to specifications follow the rules in ISO 14253-1 [6]. These rules require stringent 100% guardbanding of the expanded measurement uncertainty. Though the ISO 14253-1 rules are being included in most new ISO metrology standards, they still have not been accepted by industry and are often misunderstood. In this paper, we will take a close look at what these rules mean for CMMs and the relationship between customer and supplier.

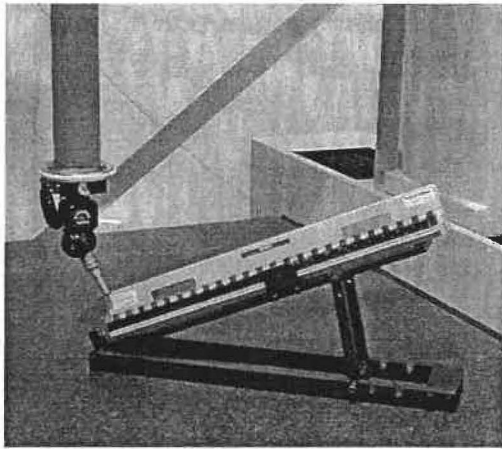


Figure 1. Test setup for E in ISO 10360-2.

The primary test in 10360-2 is quite simple. A series of length standards, usually a single step gage or a collection of gage blocks, are measured along seven different measurement lines. A typical setup for one of these seven orientations is shown in Figure 1. A simple first-order equation is usually used by the machine manufacturer to specify the worst possible error. In recent years, ISO has started using the term *Maximum Permissible Error* [12], or MPE_E , as the specification or tolerance for these measured errors. A typical machine specification for the size measuring error, E , following the new ISO 10360-2, might look like $MPE_E = 1.9 + 3L/1000 \mu\text{m}$, where L is in mm.

The difference between the 1994 and 2001 standards is in how actual measured errors, E , are compared to the MPE_E specification. Figure 2 shows measured results compared to the specification to determine conformance. As can be seen in the figure, given the exact same specification and measured results, a CMM that was in tolerance according to the 1994 standard could now be out-of-tolerance using the 2001 standard given a particular level of uncertainty. For this reason, uncertainty has now, quite suddenly, become much more interesting to all parties involved with buying, selling, testing, and calibrating CMMs.

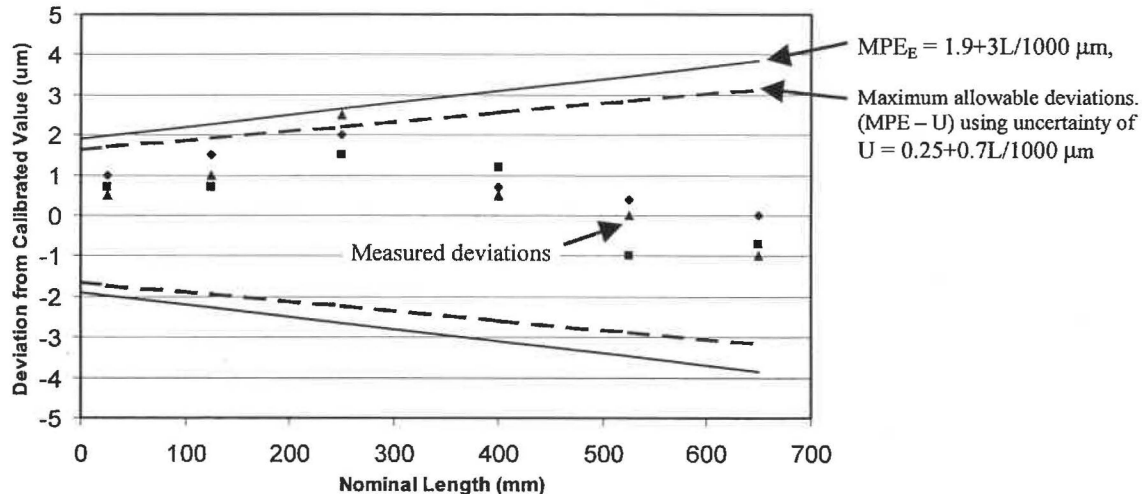


Figure 2. Typical results plot showing an example ISO 10360-2 size specification, $MPE_E = 1.9 + 3L/1000 \mu\text{m}$, represented by the solid lines, and example measured deviations. The new 2001 standard requires stringent 100% guardbanding following ISO 14253-1. Using an example expanded uncertainty of $U = 0.25 + 0.7L/1000 \mu\text{m}$, the dashed lines represent the new limit for the deviations. Following the new standard, one point, at $L=250$ mm, is out of tolerance. This CMM would pass specification with the old 1994 standard but does not using the 2001 version.

3 Measurement Uncertainty

The concept of quantitative estimates of measurement uncertainty is relatively new to the world of dimensional metrology. The *Guide to the Expression of Uncertainty in Measurement*, or GUM [1], has been around in its current form for about 10 years. Since its publication, the GUM has been widely used by national metrology institutes worldwide (for example see [13]). However, only in recent years did uncertainty reach a wider audience. The growth of uncertainty is primarily due to quality systems requirements for ISO 17025 [2] accreditation of external calibration providers for the automotive industry. This trend started in the United States with the publication of the Third Edition of QS-9000 [14] and has grown internationally with ISO/TS 16949 [3]. These standards require that providers of calibration, test, and inspection results be accredited to ISO 17025, and ISO 17025 requires uncertainty.

Commercial laboratories and on-site calibration services around the country have had to manage the requirements of ISO 17025. The biggest technical issue for implementation has been understanding and estimating uncertainty. Many laboratories, including those with experienced metrologists, have had to go to training courses or hire consultants just to handle the issue of uncertainty. Even among experts, opinions still differ on the techniques and approaches to uncertainty. The result is the potential for widely varying uncertainty estimates for the same measurements. This has not been a huge commercial problem, however, as most customers also do not understand uncertainty and often ignore the value.

During the same time period (the late 1990's) that ISO 17025 requirements became common, another group of experts in the ISO dimensional metrology standards community, ISO TC213, were coincidentally working on other requirements using measurement uncertainty. Though not without controversy, in 1998 the ISO 14253-1 standard was published with the default rule for accounting for uncertainty when determining conformance to specifications. This rule is now being used in most new ISO metrology standards, including ISO 10360-2:2001.

The argument in favor of ISO 14253-1 is straightforward. In cases where one party measures some specific quantity and reports the value against some specification, all too often the uncertainty is much too great to have much confidence in the conformance decision. Even in the world of ISO 17025 accreditation, this problem continues. The decision rule in ISO 14253-1 eliminates the problem and puts the burden of uncertainty on the party making the measurement.

The problem with implementing ISO 14253-1 is also straightforward. First, clear and concise metrology standards, like ISO 10360-2, are now requiring decision rules with uncertainty. Secondly, the primary purpose of the metrology standards is to provide a means for customers to make fair comparisons between competing metrology products and to understand inherent error sources. Third, uncertainty has continued to be a challenge, even among metrology experts, and results can vary widely. The result is that uncertainty is adding huge variation in implementing the standards and thereby destroying the primary purpose of the standards. In the next section we will discuss this specifically for CMMs.

In addition, as mentioned above, uncertainty has not necessarily been a major commercial issue in the past; however, this was before any requirement for accounting for uncertainty. With ISO

14253-1, measurement uncertainty can become a major commercial issue. The uncertainty in calibrating and testing an instrument now has equal weighting to the actual measured errors from the instrument. Just like metrology companies compete on product specifications today, ISO 14253-1 requires competition in the area of uncertainty. Competition in an area with poor understanding and lack of common practices can lead to confusing results. In addition, uncertainty has not often been particularly small compared to product tolerances, and therefore the industry could see increasing tolerances or more difficulty in meeting current tolerances.

4 Uncertainty, Calibration, Testing, and Decision Rules

Mathematically, the requirement to account for uncertainty is quite simple. The problem, however, resides in what to include in the process of estimating the uncertainty. Over the years, the national metrology institutes and major international accreditation bodies have reached some level of agreement regarding uncertainty in the world of calibrating dimensional metrology gages and instruments. This situation changes dramatically, however, when suddenly uncertainty is a competitive commercial issue, as is created by ISO 14253-1.

Additionally, the entire philosophy of ISO 14253-1 is being questioned relative to the difference between calibration and test. A new philosophy being considered in ISO TC213 and recently published in ASME B89.7.3.1 [15], the U.S. response to ISO 14253-1 (*note: the U.S. voted against ISO 14253-1*), is that testing to specification is a very different action than calibration and therefore the uncertainty is also different. The concept is that the uncertainty of testing should only include sources of uncertainty introduced by the party doing the testing, and any sources of uncertainty related to the instrument being tested should not be included in the uncertainty analysis, as is commonly done in calibration today. Though not explicitly stated, this concept therefore raises the question regarding calibration verification versus testing, and this question remains unanswered today.

Complicating this matter is the view of testing versus calibration from the perspective of ISO 17025 accreditation. These two areas are also seen as being different, but not for the conformance reasons as discussed above. For accreditation purposes, measurements that are done on measuring instruments and gages are calibrations, regardless of whether or not the results are compared to a specification. The difference with testing lies in the rigor put towards uncertainty and traceability. If the item being measured will be used as a gage, or in any manner providing traceability to any part of a measuring system, then the item needs to be calibrated, and not just tested.

One possible consideration is that there should be two different uncertainty values, one for testing to specification and one for calibration. In some cases, the measurements may be identical and in some cases they may be different. In the case of CMMs, it is quite common to use the performance test standards, like ISO 10360-2, as the calibration standard. In this case, both the test uncertainty and the calibration uncertainty would be reported for the same measurements, though the uncertainty would be different. This concept needs further research.

5 Uncertainty and Decision Rules in ISO 10360-2:2001

What matters in the scope of this paper is how uncertainty is to be handled relative to the new ISO 10360-2:2001 standard. The working group responsible for this standard, ISO TC213 working group 10 on CMMs, is currently preparing a new document that provides guidance to uncertainty for the ISO 10360 series of standards. This seems to imply that the standards do not stand alone and cannot be properly implemented today. That guidance document is years away from being available and therefore the CMM industry must cope with the situation as it is today.

The ISO 10360-2 standard itself provides some direction on uncertainty, which may help or may further complicate the situation. The standard is clear that the following uncertainty issues must be included: (1) the calibration of the material standard used in testing the machine and (2) the alignment of the material standard. Since alignment issues are normally negligible, then the only consideration for uncertainty, according to the standard as written, is the uncertainty of the calibration of the gages used to test the CMM. This is the approach shown in Figure 2, where a step gage with an expanded uncertainty for its calibration of $U = 0.25 + 0.7L/1000 \mu\text{m}$ is used to test the CMM.

This uncertainty is clearly not the same as the uncertainty of calibration, if the ISO 10360-2 procedure is used as a calibration procedure for a CMM. There are a number of issues related to temperature and machine repeatability that would normally be considered in a calibration uncertainty analysis. In addition, there is some concern regarding what ISO 10360-2 means by the phrase "calibration uncertainty" of the material standard. Some experts say this also includes the uncertainty that arises when the gage is used at a temperature other than the standard 20°C. Since a material standard is usually calibrated at 20°C, if it is used at other temperatures, then the calibration is not necessarily valid and additional uncertainty is present due to the uncertainty in the knowledge of the coefficient of thermal expansion. While this uncertainty may be small in controlled environments it can dominate the uncertainty when CMMs are installed in typical shop floor environments.

In the end, there is currently confusion on what may or may not be included in the uncertainty analysis when ISO 10360-2:2001 is used. The end result is that customers have lost the ability to quickly and easily compare CMM specifications. Instead, they will need to acquire complicated information regarding how individual manufacturers or calibration services will be interpreting the standard and applying the uncertainty. It is not expected that most customers will have this level of understanding of the standards, and therefore the ability to use the standard for comparing CMMs has been lost.

6 Conclusions

The dimensional metrology industry is currently dealing with many new concepts and much change. Most of the change is occurring quickly and industry is in transition. The concepts of decision rules, in particular ISO 14253-1, were standardized but not necessarily accepted or tested by industry. We are at a point now where we must look at the results of the recent changes and evaluate how they are working for the metrology industry. One observation is that metrology standards must include clear decision rules along with detailed information regarding accepted

methods for the uncertainty analysis. The specification, the decision rule, and the uncertainty are a matched, mutually dependent, set that cannot be looked at individually. Since uncertainty now has importance equal to the test methods included in the standards, it is imperative that the uncertainty be described in equal detail. If these issues are not addressed, then we risk the situation that we have today with ISO 10360-2:2001 – the usefulness of the standard, and all the hard work that has gone into it, has been lost due to a vague implementation of a decision rule.

7 References

1. Guide to the expression of uncertainty in measurement. International Organization for Standardization, 1995.
2. ISO/IEC 17025:1999. General requirements for the competence of testing and calibration laboratories.
3. ISO/TS 16949:2002. Particular requirements for the application of ISO 9001:2000 for automotive production and relevant service part organizations.
4. ISO 10360-2. Acceptance and reverification tests for CMMs, part 2: CMMs used for measuring size.
5. ASME B89.4.1-1997. Methods for performance evaluation of coordinate measuring machines.
6. ISO 14253-1:1998. Decision rules for proving conformance or non-conformance with specification.
7. ISO 10360-1: Acceptance and reverification tests for CMMs, part 1: vocabulary.
8. ISO 10360-3: Acceptance and reverification tests for CMMs, part 3: CMMs with the axis of a rotary table as the fourth axis.
9. ISO 10360-4: Acceptance and reverification tests for CMMs, part 4: CMMs used in scanning measuring mode.
10. ISO 10360-5: Acceptance and reverification tests for CMMs, part 5: CMMs using multiple stylus probing systems.
11. ISO 10360-6: Acceptance and reverification tests for CMMs, part 6: Estimation of errors in computing of Gaussian associated features.
12. International vocabulary of basic and general terms in metrology. International Organization for Standardization, 1993.
13. Taylor BN and Kuyatt CE. NIST Technical Note 1297. Guidelines for evaluating and expressing the uncertainty of NIST measurement results, 1994.
14. QS-9000, Quality system requirements, Third Edition, 1998.
15. ASME B89.7.3.1-2001. Guidelines for decision rules: considering measurement uncertainty in determining conformance to specifications.

Novel 3D analogue probe with a small sphere and low measurement force

F. Meli, M. Bieri, R. Thalmann, M. Fracheboud, J-M. Breguet*, R. Clavel*, S. Bottinelli***

Swiss Federal Office of Metrology and Accreditation (METAS), 3003 Bern-Wabern, Switzerland (www.metas.ch).

* Institut de Production et Robotique (IPR-LSRO), EPFL, 1015 Lausanne, Switzerland (lsro.epfl.ch).

** MECARTEX, Z.I. Zandone, 6616 Losone, Switzerland (www.mecartex.ch).

Abstract

A new 3D touch probe for coordinate measuring machines (CMM) with exchangeable probes with spheres in the diameter range of 0.1 mm to 0.3 mm and probing forces below 0.5 mN was developed. The device is based on parallel kinematics with flexure hinges and is manufactured out of a single piece of aluminium. All rotational movements of the probing sphere are blocked. The remaining possible translational motion is separated into its xyz-components, which are each measured by an inductive sensor. All axes have the same orientation with respect to gravity. The stiffness is isotropic with a value of only 20 mN/mm, while the effective moving mass is about 7 g. First experiments with the 3D touch probe were performed on a linear measuring machine equipped with a laser interferometer. The standard deviation of repeated measurements, e.g. the difference between left and right probing on a 5 mm gauge block, was in the order of 5 nm.

Introduction

In the last years CMMs have become versatile and widespread metrology tools. Today's CMMs can efficiently perform very complex measurement tasks. However, with the ongoing miniaturisation in the mechanical and optical production there is a new demand for highly accurate geometrical measurements on small parts. New instruments should have low uncertainties and probe the objects with very small spheres using very low contact forces. Up to now, the limiting factor for the application of CMMs on small parts was mainly the probe head and therefore new developments are needed [1, 2].

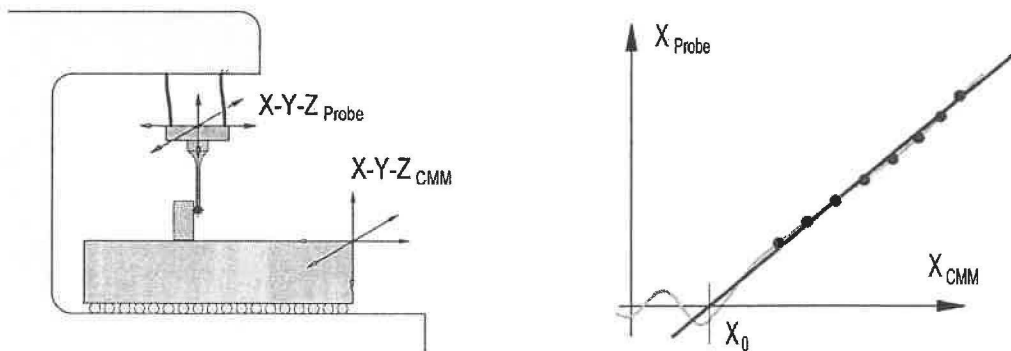


Figure 1: Measuring principle of a CMM (left) and probing data used to determine the force free contact point of the probing sphere (right).

The point of contact between the probing sphere and the sample surface should be obtained by measuring probe deflections at several CMM positions. This allows extrapolation to zero deflection where also the contact force is zero (Fig. 1 right). In the context of a Swiss TOP NANO 21 research project the EPFL, the industrial partner MECARTEX and METAS developed a new 3D touch probe for measurements on small objects.

Probing force and surface damage

The relatively large probing forces of conventional probe systems may damage the surface of the work piece and thus falsify the measurement result. Figure 2 shows on the left an atomic force microscope image of such a plastic surface deformation on an aluminium test piece. It was probed with a conventional 3D touch probe with a sphere of 0.6 mm diameter resulting in an indent with 330 nm depth.

If a probe sphere with a diameter in the order of 0.1 mm is to be used without leaving any permanent surface indentation, the force needs to be about 100 times smaller than with today's commercial probe systems (Fig. 2 right). This means the stiffness of the probing system has to be very small e.g. 20 mN/mm to allow still some probe deflection at these low forces (typ. 20 μ m). The situation is even more critical with respect to dynamic forces that act when the sphere hits the surface upon first contact. Therefore the effective moving mass needs also to be as small as possible to allow reasonable approach speeds.

Construction

Based on parallelograms and flexure hinges a new kinematic structure was designed for the probe head. This structure leaves the probing sphere exactly three degrees of freedom. The rotational movements are blocked and the translational motion is separated in its xyz-components, which are each measured by an inductive sensor (Fig 3). All axes have the same orientation with respect to gravity and provide the same probing force in all directions. The main part of the structure is manufactured out of a single piece of aluminium using electro discharge machining. Therefore the most critical part does not need to be assembled. The flexure hinges have a thickness of only 60 μ m resulting in a stiffness of 20 mN/mm. The effective moving mass is 7 g. Due to the low stiffness, the deformation caused by gravity needs to be compensated. For this purpose

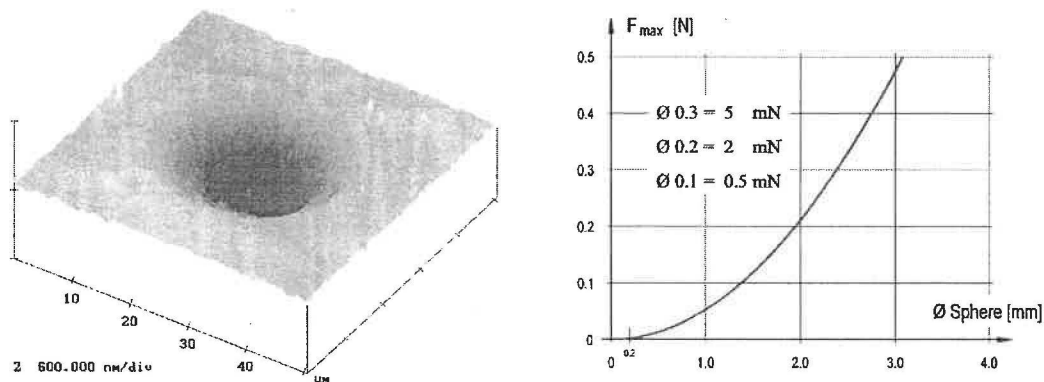


Figure 2: Plastic deformation on an aluminium surface after probing with a conventional probe (left) and maximal admissible probing forces for various sphere diameters at 1000 MPa contact pressure (right) [3].

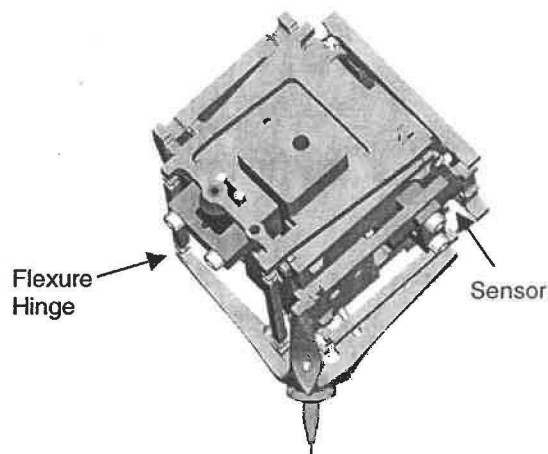


Figure 3: Kinematic structure of the 3D touch probe.

an adjustable system with permanent magnets was developed.

The measurement range is ± 0.2 mm while the mechanical limits allow a range of ± 0.5 mm. The probing element is magnetically attached to the head and positioned by means of three balls in three grooves (Fig. 4 left). The magnetic holding of the probing element allows an easy replacement and acts also as a mechanical fuse. Therefore the handling of this highly sensitive device remains quite easy.

A small moving mass is important to keep the dynamic contact forces low while maintaining reasonable approach speeds. Model calculations showed that the effective mass (7 g) of the probe is still too high. A small additional mechanical filter element was developed to reduce the effect of dynamic forces. Its stiffness is almost equal in all directions and roughly 100 times higher than that of the probe head but it has a very low effective mass (Fig. 4 right). Typical approach velocity is thus 1 mm/s.

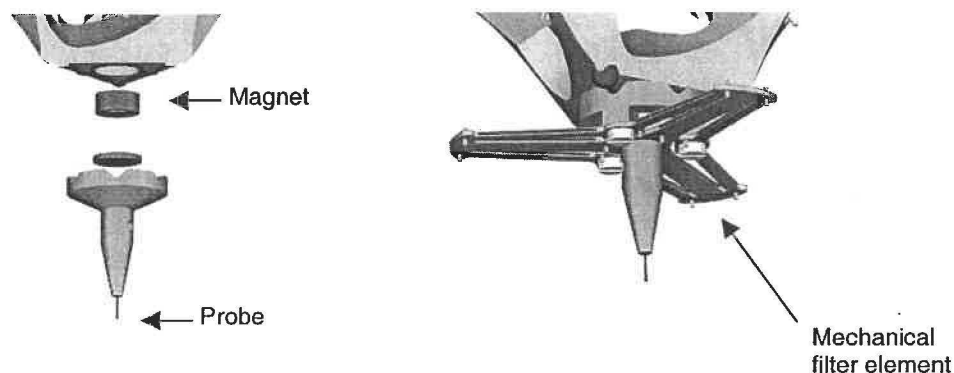


Figure 4: Magnetic holding of the probing element (left) and mechanical filter (right).

Experimental Results

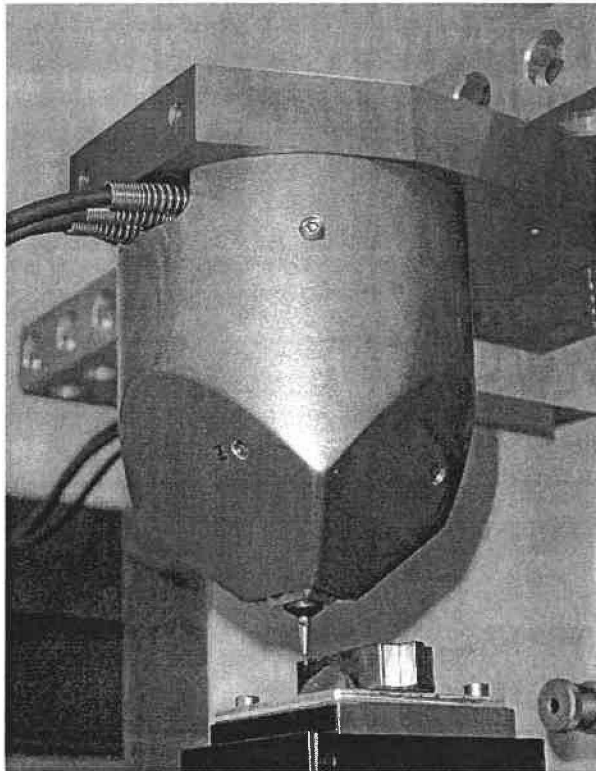


Figure 5: Experimental arrangement for the probe test on the LMM.

The full performance of the new probe can only be measured on a CMM with equal or better performance than the probe itself. However, at the moment we have no such ultra precision CMM available. Therefore the first experiments with the new 3D touch probe were performed on a linear measuring machine (LMM) equipped with a laser interferometer (Fig 5). In this way only probings in a horizontal plane could be made. However, due to the special orientation of the probe coordinate system all 3 sensors of the probe head were involved in these test measurements. The test consisted of probing a known 5 mm gauge block on the left and right side. The difference between the two points minus the gauge block length is the probe constant, which is essentially the sphere diameter. The repeatability of the probe constant is an important parameter for a 3D touch probe. In our experiments the standard deviation of 5 such measurements was always in the order of 5 nm. This value even includes

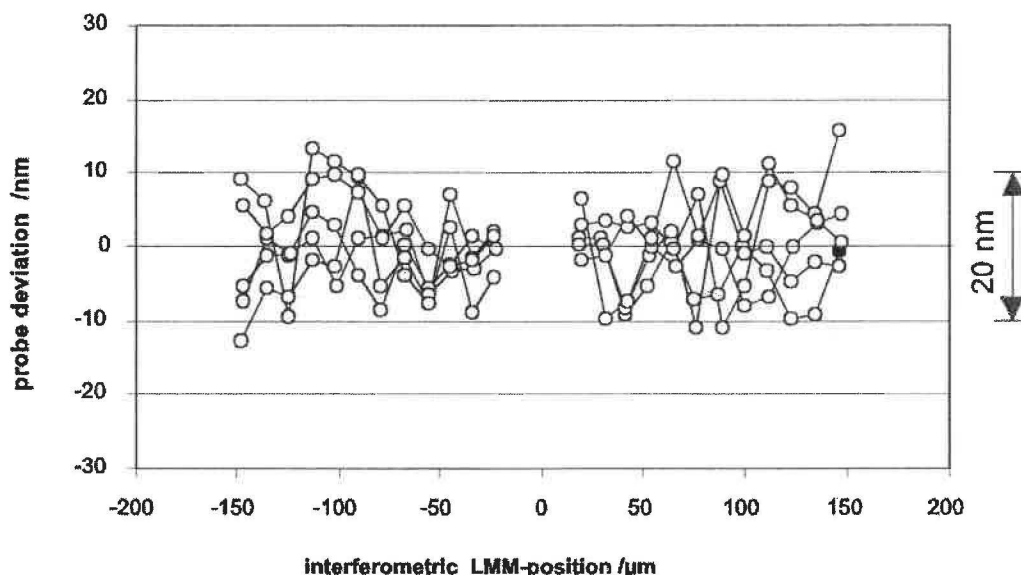


Figure 6: Deviation from linearity of 5 touch probe measurements for the left and right side of the gauge block.

interferometer noise and machine instability like vibration and drift. Also for large probe deflections up to 150 μm the linearity of the probe signal remains very good (Fig. 6).

Conclusions

A new 3D touch probe for CMMs with exchangeable probes and low probing forces was developed and a patent has been filed. The innovative design is based on a parallel kinematics with flexure hinges. First test measurements were very successful. With probing forces smaller than 0.5 mN the repeatability was in the order of 5 nm.

For the full characterisation of the probe needs a CMM with comparable performance. We plan therefore to incorporate the probe head into a new ultra precision CMM [4] at METAS. The goal is to offer calibration and measurement services for small parts up to a size of about 50 mm in the near future.

References

- [1] U. Brand, S. Cao, W. Hoffmann, T. Kleine-Besten, P. Pornnoppadol, S. Büttgenbach, Proc. of 2nd euspen Int. Conf., p266-269, May 2001, Turin, Italy.
- [2] H. Haitjema, J.K. van Seggelen, P.H.J. Schellekens, W.O. Priel, E. Puik, Proc. of Memstand Int. Conf., p218-228, February 2003, Barcelona, Spain.
- [3] W.P. van Vliet, P.H. Schellekens; Annals of the CIRP 45, 483-487, 1996.
- [4] T. Ruijl, J. Franse, J. van Eijk, "Ultra precision CMM aiming for the ultimate concept", Proc. of 2nd euspen Int. Conf., p234-237, May 2001, Turin, Italy.

A STUDY FOR DEVELOPMENT OF SMALL-CMM PROBE DETECTING CONTACT ANGLE

Ichiro Ogura, Yuichi Okazaki
Fine Manufacturing System Group
Institute of Mechanical Systems Engineering
National Institute of Advanced Industrial Science and Technology (AIST),
Tsukuba 305-8564, Japan

1. Introduction

This study describes the development of a probe for a micro coordinate measuring machine (CMM).

To measure micro-parts in the nanometer size range, the concepts of a nano-CMM¹⁾ and an ultra precision CMM²⁾ have been proposed, and there have been many interesting studies on the development of novel probes³⁾⁻⁵⁾.

In order to measure the 3-dimensional profiles of micro-parts, that have complex or curved shapes, it is necessary to detect not only the making of contact by the probe ball, but also the contact angle. The location of the surface can then be determined from the contact angle and the radius of the probe ball. The normal vector of the profile is described by the inclination direction ψ in the ϕ rotated x - y plane along the z -axis (z - ϕ plane). Then two angles, ϕ and ψ , are needed to determine the contact position.

Some methods exist to detect the contact angle mechanically. One such method employs a 3d-sensor based on a silicon boss-membrane with piezo resistive transducers⁶⁾. Another uses elastic hinges made by a micro-electro-mechanical system (MEMS) technique⁷⁾.

We conducted this investigation on a two-dimensional micro probe⁸⁾. The probe we developed could measure a contact point and a contact angle simultaneously in a two-dimensional plane, using active circular rotation. In this study, further developing the previous probe, we propose a novel probe, that detects the contact angle in three-dimensions, developed a prototype probe system, and conducted a preliminary experiment to verify the principle. The results show that accurate evaluation of profiles is possible.

2. Measurement principle

Fig. 1(a) and (b) show the measurement principle of the proposed system. In this system, most contact-type probes could be used, such as the electrical touch type, optical type, or strain gauge type. However the probe must be able to detect contact from all directions in the measuring plane.

This method uses two procedures to measure the contact angle as follows.

STEP 1(Fig. 1(a)): Applying $(A \cos \omega t)$ motion to the x -axis, $(A \sin \omega t)$ to the y -axis, and no motion to the z -axis, the probe moves circularly with radius A in the x - y plane. When the probe contacts the profile, a periodic contact signal will be detected. The angle ϕ can be calculated by comparing the phase of rotation and the mid point of a contact signal.

STEP 2 (Fig. 1(b)) : Applying $(A \cos \phi \cos \omega t)$ to the x -axis, $(A \sin \phi \cos \omega t)$ to the y -axis, and $(A \sin \omega t)$ to the z -axis causes the probe to rotate in the z - ϕ plane. As in STEP 1., the angle ψ can be determined.

After determining two angles, the contact coordinate is adjusted to take into account the radius of probe the ball and the amplitude A . By applying this method to all measuring points, precise measurement is accomplished.

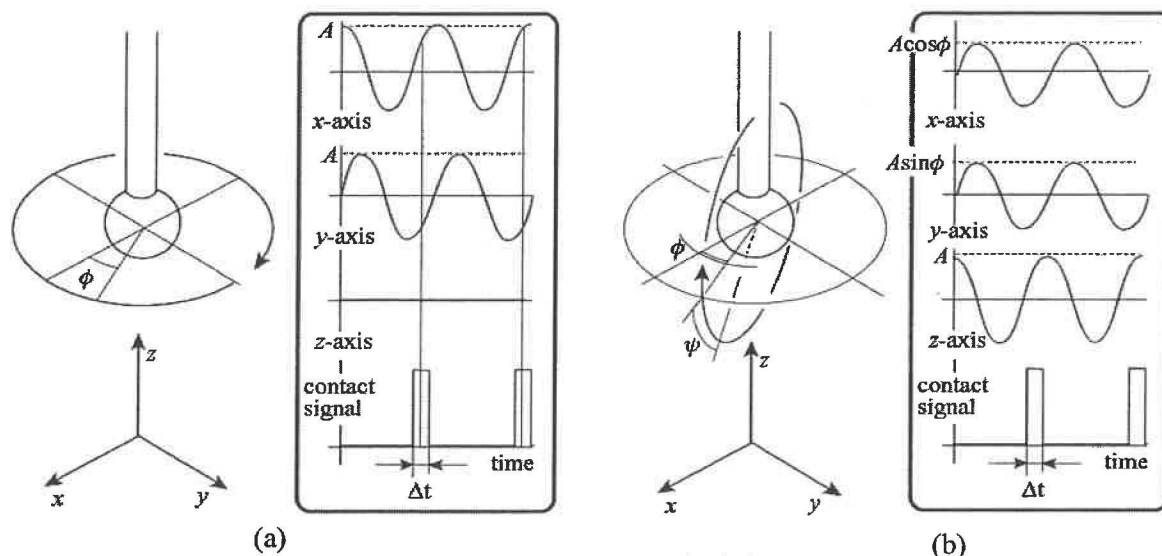


Fig. 1 Measurement principle

To obtain an equal response from all contact directions, the rotating motion should ideally be perfectly circular and the probe should have a high-precision circular profile. However, if the probe motion or probe profile have some error, measurement accuracy can be confirmed by a calibration technique.

3. Set-up of prototype probe system

We developed a macro probe model to confirm our proposed method. Fig. 2 shows the schematic of the probe system. This system has a ball bearing probe with 350 μm diameter. This probe is an electric touch type probe. Three piezoelectric actuators move the probe circularly at 10 Hz with a 3 μm radius of rotation. Each axis has a laser displacement sensor and the actuators are moved by feedback control.

Fig. 3 shows the stage. This stage has x-y plane feedback control with interferometers. A stepping motor stage is used for coarse movement and a piezoelectric actuator stage is used for fine movement. A personal computer acquires displacements from the interferometers through a GP-IB interface, calculates the feedback and controls the stages.

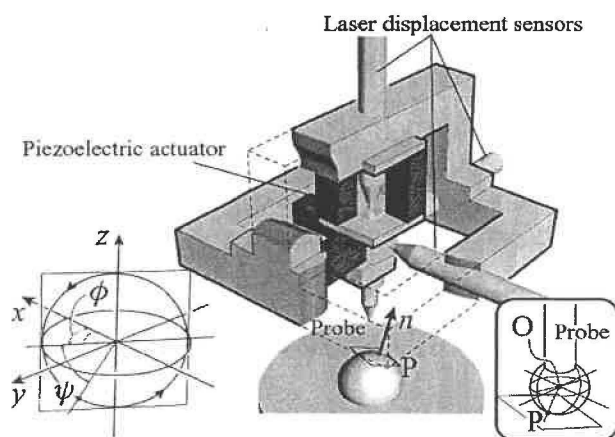


Fig. 2 Schematic of probe system

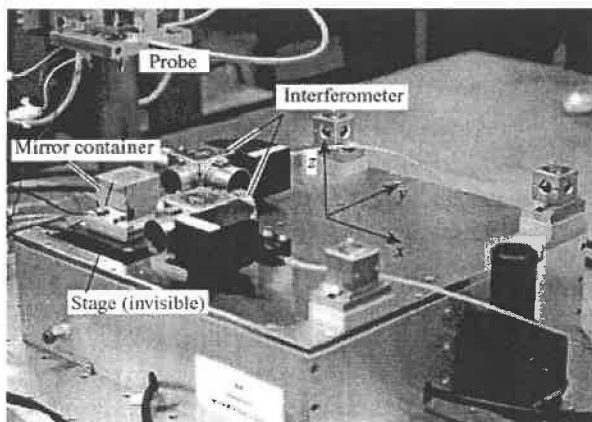


Fig. 3 Photograph of stage

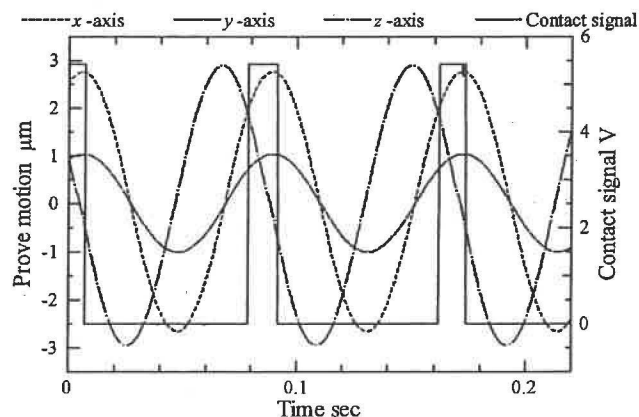


Fig. 5 Probe moving and contact signal

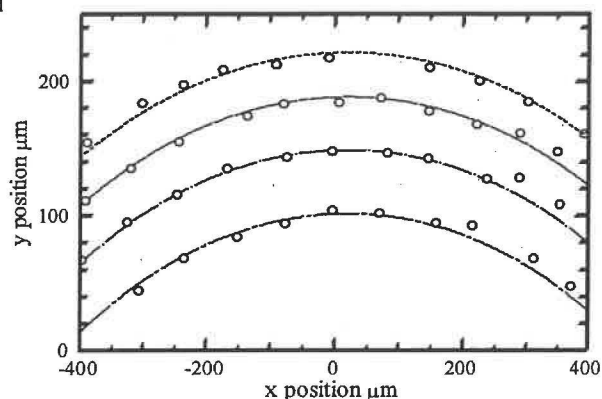


Fig. 6 Results of profile measurement experiment

The profile measurement experiment was performed for the ball bearing. Four z heights were selected and the profile was measured in each x - y plane. The interval of z height was $100\text{ }\mu\text{m}$. Fig.6 shows the results of the experiments. This figure plots calculated contact points in each x - y plane and expected profiles calculated from the z height. The results show good agreement with the expected profiles. The maximum error was $10\text{ }\mu\text{m}$. Since the radius of the probe ball is $350\text{ }\mu\text{m}$, the estimated maximum error becomes $700\text{ }\mu\text{m}$ without contact position compensation. The proposed method reduces this error by about 98.6%, and establishes the validity of the proposed method.

5 Conclusion

We have proposed a new probe for a micro CMM that can simultaneously detect the contact point and contact direction. A prototype probe system was developed and a preliminary experiment was performed. The results of the experiment confirmed the validity of our method.

References

- 1) K. Takamasu, et al.: Basic Concepts of Nano-CMM (Coordinate Measuring Machine with Nanometer Resolution), Proc. of Japan-China Bilateral Symposium on Advanced Manufacturing Engineering (1996) 155.
- 2) T. Ruijl, et al.: Ultra Precision CMM Aiming for the Ultimate Concept., Proc. of 2nd euspen International Conference (2001) 234.
- 3) U. Brand, et al.: Development of a special CMM for dimensional metrology on microsystem components., Proc. of ASPE 2000 (2000) 542.
- 4) T. Masuzawa, et al.: Twin-Probe Vibroscanning Method for Dimensional Measurement of Microholes., Annals of the CIRP 46, 1 (1997) 437.
- 5) Y. Takaya, et al.: Nano-Positional Detection Using Laser Trapping Probe for Microparts, Proc. of ASPE 2000 (2000) 584.
- 6) U. Brand, S. Cao, W. Hoffmann et al : A Micro-Probing System for Dimensional Metrology on Microsystem Components, Proc. of 2nd euspen International Conference, (2001), 266.
- 7) H. Haitjema, W. O. Pril and P. H. J. Schellekens : Development of a Silicon-Based Nanoprobe System for 3-D Measurements, Annals of the CIRP, 50, 1, (2001), 361.
- 8) I. Ogura and Y. Okazaki : Development of micro probe for micro-CMM, Proc. of ASPE 2002 (2002) 349.

A Trinocular Vision Probe for Sculptured Surface Measurements

G.X. Zhang, H.W. Zhang, Z. Liu, J.B. Guo, X. S. Zhao, Y.M. Fan, Z.R. Qiu, X.F. Li, Z. Li
State Key Laboratory of Precision Measuring Technology and Instruments,
Tianjin University, Tianjin 300072, China

Keywords: Sculptured surface measurement; trinocular vision probe; camera calibration; matching technique; reconstruction

1. Introduction

Reverse engineering of free-form surfaces is one of the most challenging technologies in advanced manufacturing [1]. With the development of industry more and more sculptured surfaces, such as molds and dies, turbine blades, are required to measure quickly and accurately. Optical non-contact probes possess many advantages, such as high speed, no measuring force, no deformation caused, in comparison with contact ones [2]. The ability of stereo vision probe with CCD cameras in gathering a large amount of information simultaneously makes it the most popularly used one in sculptured surface measurements. As a common practice two CCD cameras are used to form a binocular system and the geometric features of the object are obtained by matching two images captured by these cameras. The following deficiencies were discovered in such a system [3]. A mismatch might occur when certain part of the object is hidden by some obstacles or the images are blurred or noisy. Mismatches also might happen in case of having repeating sceneries or little change in the grey level of sceneries. The accuracy of measurement is deteriorated when the angle formed by the measured curve and epipolar line used for image matching is small. To overcome all these problems a line structured light trinocular vision probe for sculptured surface measurements is developed. It distinguishes itself by high efficiency, high accuracy and reliability, as well as applicability for on-line measurement of complicated sculptured surfaces.

2. Working Principle

The working principle of the trinocular vision probe is shown in Figure 1. A light stripe emitted from the laser head is projected on the surface measured. The light stripe is deformed in accordance with the form of sculptured surface. Three CCD cameras are used to capture the images of the deformed light stripe. The form and the position of the surface are determined by matching these images. The main trouble in measuring high-reflective sculptured surfaces is that the specular light is much stronger than the diffused one. Two images might be formed in each CCD camera. One is formed by the specular light, another by diffused light. For solving this problem a polarizer and three analyzers are used. The light stripe projected on the surface is linearly polarized. The specular light will be also linearly polarized whereas diffused light forms a polarization ellipsoid. The polarization directions of the analyzers are perpendicular to that of polarizer. The specular light is eliminated in large degree and only the diffused light can reach three CCD cameras.

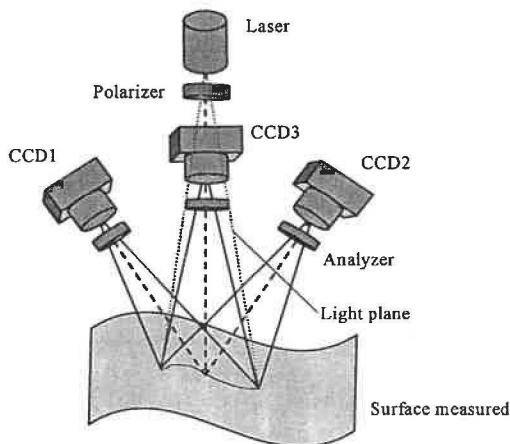


Figure 1 Diagram of the trinocular probe

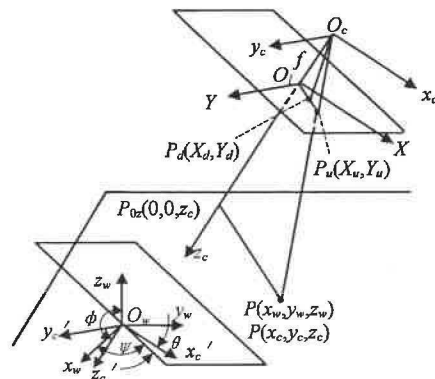


Figure 2 Coordinate transformation between camera and workpiece systems

3. System optimization

In Figure 2, only one camera is shown. $O_w x_w y_w z_w$ is the workpiece system and $O_c x_c y_c z_c$ is the camera system. The coordinate transformation relations between two systems can be expressed as

$$\begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} = R \begin{bmatrix} x_w \\ y_w \\ z_w \end{bmatrix} + T \quad \text{or} \quad \begin{bmatrix} x_w \\ y_w \\ z_w \end{bmatrix} = R' \begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} + T' \quad (1)$$

$$\text{and } R = \begin{bmatrix} r_1 & r_2 & r_3 \\ r_4 & r_5 & r_6 \\ r_7 & r_8 & r_9 \end{bmatrix}, \quad R' = R^{-1} = \begin{bmatrix} r'_1 & r'_2 & r'_3 \\ r'_4 & r'_5 & r'_6 \\ r'_7 & r'_8 & r'_9 \end{bmatrix}, \quad T = \begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix}, \quad T' = \begin{bmatrix} T'_x \\ T'_y \\ T'_z \end{bmatrix} \quad (2)$$

where R and R' are rotational matrices, T and T' are translation matrices. All components r_i and r'_i ($i=1\sim9$) in R and R' are functions of three Euler angles ϕ, ψ, θ . From perspective imagery it can be derived

$$X = f \frac{x_c}{z_c}, \quad Y = f \frac{y_c}{z_c} \quad (3)$$

where X and Y are coordinates of a point on the image plane and f is the camera constant. From (1), (2) and (3)

$$x_w = \frac{(y_w - T_y')(r'_1 X + r'_2 Y + r'_3 f)}{r'_4 X + r'_5 Y + r'_6 f} + T_x', \quad \text{and} \quad z_w = \frac{(y_w - T_y')(r'_1 X + r'_8 Y + r'_9 f)}{r'_4 X + r'_5 Y + r'_6 f} + T_z' \quad (4)$$

Both x_w and z_w are functions of $(X, Y, \phi, \psi, \theta, f, T_x', T_y', T_z')$. By taking partial derivatives it can be calculated

$$\Delta z_w = \frac{|f(T_y' - y_w)|}{(Y \cos \phi + f \sin \phi)^2} |\Delta Y| = \frac{f(T_y' - y_w)}{(f^2 + Y^2) \sin^2(\phi + \tan^{-1} \frac{Y}{f})} |\Delta Y| \quad (5)$$

In discussion of the optimal arrangement it is reasonable to assume $Y=0$ when $y_w=0$ and the optical axis of the camera passes through point O_w . In this case $T_y' = T_z' \tan \phi$ when $\theta = \psi = 0$, and Formula (5) takes form

$$\Delta z_w = \frac{2fT_z'}{f^2 \sin 2\phi} |\Delta Y| \quad (6)$$

Δz_w gets its minimum under fixed ΔY when $\phi = \pi/4$. However the larger the ϕ the larger the dimension of the probe. For reducing the dimension of the probe $\phi = \pi/6$ is taken in our design. Three CCD cameras form a regular triangle as shown in Figure 3a. 2α is the view angle of the camera. The common zone of view is shown by shadow area in Figure 3b and

$$\delta = 2\gamma = 2(\pi/2 - \sigma) = \pi - 2 \tan^{-1} \left(\frac{\sqrt{3}t}{2d'} \right) = \pi - 2 \tan^{-1} \left(\frac{\sqrt{3}t}{2\sqrt{d^2 + (t/2)^2}} \right) \approx \pi - 2 \tan^{-1} \frac{B}{2d} \quad (7)$$

where d is the object distance. The common view zone increases with the increase of object distance d and decrease of base line length B . After calculation it can be also shown the depth of field increases with the increases of focal

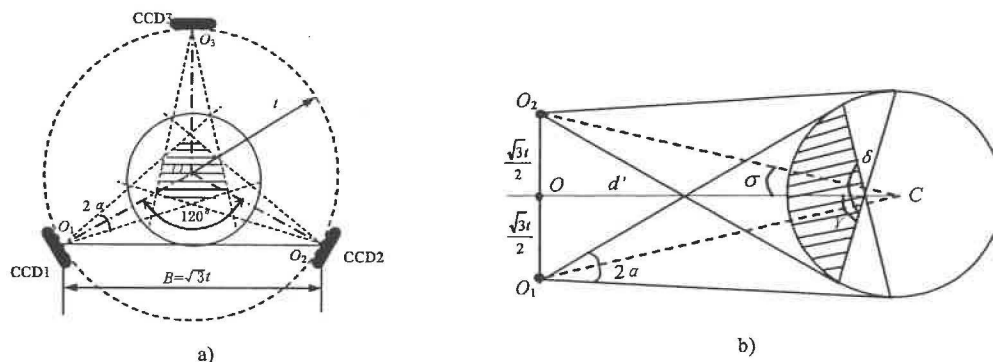


Figure 3 View area of the probe

length, and the decreases of magnification factor, numerical aperture, and diameter of the incident pupil. All these factors should be considered simultaneously and some compromises should be made in the probe design.

4. Camera calibration

In order to obtain the corresponding relationship between the positions of the points in space and the pixel numbers in the images camera calibration is essential. In the current time Tsai's two step method [4] is the most popularly used method among techniques for calibrating camera parameters. This method determines most of the camera parameters including camera constant f , coordinates of the image center (C_x, C_y) , lens distortion coefficient k and position of the camera with reference to the artifact, based on the radial alignment constraint by using nonlinear searching. But this method cannot determine the uncertainty of the scale factor in horizontal direction s_x . For solving this problem a technique based on a virtual 3-D artifact shown in Figure 4 is proposed in this paper.

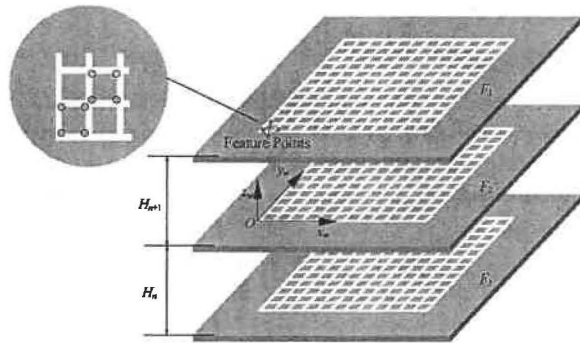


Figure 4 3-D virtual artifact

Since 3D artifact is difficult to make a 2D artifact in form of a grid plate is applied in our study. The grid plate is mounted at different heights during the calibration process to form a virtual 3D artifact. The following equations can be written.

$$\left. \begin{aligned} X'_{di} &= X_{di} s_x = (X_{fi} - C_x) d'_x \\ Y_{di} &= (Y_{fi} - C_y) d_y \\ d'_x &= d_x N_{cx} / N_{fx} \end{aligned} \right\} \quad (8)$$

where (X_{fi}, Y_{fi}) are coordinates of i -th image point in pixels; (C_x, C_y) are coordinates of the image center in pixels; d_x and d_y are pixel intervals in x and y directions, respectively; N_{cx} and N_{fx} are number of the pixels on the CCD element and number of points sampled

by the graphic card in horizontal direction, respectively. (X_{di}, Y_{di}) and (X_{ui}, Y_{ui}) are coordinates of the distorted and undistorted images of i -th feature point in millimeters, respectively. From (1), (2), (3) and (8) we have

$$\frac{X'_d}{Y_d} = \frac{X_u}{Y_u} = \frac{x_c}{y_c} = \frac{r_1 x_w + r_2 y_w + r_3 z_w + T_x}{r_4 x_w + r_5 y_w + r_6 z_w + T_y} \quad (9)$$

$$\text{or } [Y_{di} x_{wi} \quad Y_{di} y_{wi} \quad Y_{di} z_{wi} \quad Y_{di} \quad -X'_{di} x_{wi} \quad -X'_{di} y_{wi} \quad -X'_{di} z_{wi}] L' = X'_{di} \quad (10)$$

$$L' = [a_1 \quad a_2 \quad a_3 \quad a_4 \quad a_5 \quad a_6 \quad a_7]^T = [T_y^{-1} s_x r_1 \quad T_y^{-1} s_x r_2 \quad T_y^{-1} s_x r_3 \quad T_y^{-1} s_x T_x \quad T_y^{-1} r_4 \quad T_y^{-1} r_5 \quad T_y^{-1} r_6]^T \quad (11)$$

In Formula (10) $i=1 \sim N$, N is the total number of calibrated points. All values except (C_x, C_y) are obtained from calibration measurement. The coordinates of the center of computer frame memory are taken as the initial values of (C_x, C_y) . L' can be determined by least square fitting. Since $r_1^2 + r_2^2 + r_3^2 = 1$ and $r_4^2 + r_5^2 + r_6^2 = 1$, we obtain

$$|T_y| = (a_5^2 + a_6^2 + a_7^2)^{-1/2} \quad \text{and} \quad s_x = (a_1^2 + a_2^2 + a_3^2)^{1/2} |T_y| \quad (12)$$

After s_x has been obtained Tsai's two step method can be applied to calibrate all the intrinsic and extrinsic parameters of the camera. For improving the accuracy of calibration iterations are often required.

5. Sampling strategy

Sampling strategy is important to obtain all the required data with high accuracy in a short time. The first problem here is selecting the correct scanning direction. There are two types of machined surfaces. Ground and lapped surfaces belong to the first type. There is almost no visible machined trace in certain direction. However the machined traces might be quite obvious for turned, milled and planed surfaces. In the later cases it is recommended to arrange the light stripe in the direction perpendicular to the machined traces as shown in Figure 5a and a straight line image shown in Figure 5b is obtained. When the light stripe is in the direction parallel to the machined traces as shown in Figure 5c a bright spot shown in Figure 5d might be formed.

The next question is selecting the step in scanning. An adaptive sampling strategy based on the curvature of surface in the scanning direction is developed. The step distance is determined by $S = \sqrt{8\rho h}$, where ρ is the radius of curvature and h is the allowed chord height in each sampling interval. Similar idea is applied to the data point sampled on each light stripe.

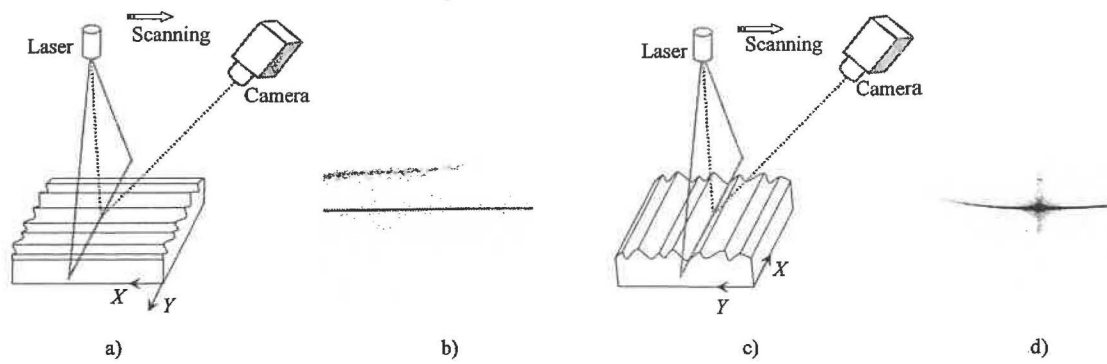


Figure 5 Scanning directions

6. Feature extraction

The image of the line stripe is a zone with certain grey distribution. The position of the extracted feature depends in large degree on the chosen threshold. The grey level $f(i, j)$ of the image at point (i, j) depends not only on the position of the point but also a lot of other factors, such as illumination, shadow, background and neighborhood grey levels. The threshold should be adaptive to these factors. A threshold technique based on the grey transition region is used in our study [5]. The effective average gradient of EAG is defined as

$$EAG = TG/TP \quad \text{and} \quad TG = \sum_{i,j \in Z} g(i, j), \quad TP = \sum_{i,j \in Z} p(i, j) \quad (13)$$

where $i, j \in Z$ means that the integrals are taken for the whole zone. $g(i, j)$ is the gradient of grey level. $g(i, j) = \sqrt{\Delta_x f(i, j)^2 + \Delta_y f(i, j)^2}$ and $\Delta_x f(i, j) = f(i, j) - f(i-1, j)$, $\Delta_y f(i, j) = f(i, j) - f(i, j-1)$ and $p(i, j) = 1$ when $g(i, j) > 0$, $p(i, j) = 0$ when $g(i, j) = 0$.

High cut grey level $f_{high}(i, j)$ is defined as $f_{high}(i, j) = Q_h$ when $f(i, j) \geq Q_h$; and $f_{high}(i, j) = f(i, j)$ when $f(i, j) < Q_h$. Low cut grey level $f_{low}(i, j)$ is defined as $f_{low}(i, j) = Q_l$ when $f(i, j) \leq Q_l$; and $f_{low}(i, j) = f(i, j)$ when $f(i, j) > Q_l$.

It is obvious the values of $EAG_{high}(Q_h)$ and $EAG_{low}(Q_l)$ depend on the values of Q_h and Q_l chosen. The values of Q_h and Q_l under which $EAG_{high}(Q_h)$ and $EAG_{low}(Q_l)$ reach their maximums are expressed by Q_{high} and Q_{low} and define the transition zone as shown in Figure 6. The average value of the grey level within this transition zone is defined as the threshold for feature extraction.

For enhancing the accuracy of feature extraction a sub-pixel edge detection algorithm based on the spatial moment theory is adopted in our work [6]. The position of the sub-pixel edge l can be calculated from

$$l = \frac{4M'_{20} - M_{00}}{3M'_{10}} \quad (14)$$

where: $M'_{10} = \sqrt{M^2_{01} + M^2_{10}}$, $M'_{20} = \frac{M^2_{10}M_{20} + 2M_{01}M_{10}M_{11} + M^2_{01}M_{02}}{M^2_{01} + M^2_{10}}$, $M_{pq} = \iint x^p y^q f(x, y) dx dy$.

7. Image matching

The position of a feature point in space cannot be determined just by its image in one camera. Image matching is an important step for determining the position of a feature point in space. For improving the accuracy and reliability of image matching both geometric constraints and grey level similarity constraint are applied. The geometric constraints include following three statements: (1) Uniqueness: Each point has a unique image point on the image plane. (2) Projection constraint: Each point on the image plane might correspond to different points in the space. However all they lie on the line connecting the optical center of the camera and the image point. (3) Light stripe constraint: The point in space must lie on the light stripe, which generates the image.

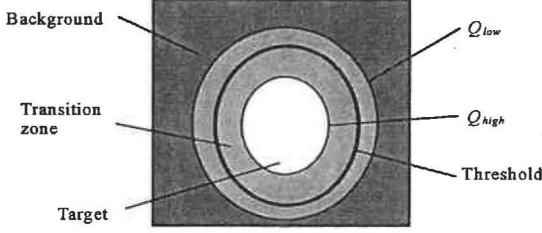


Figure 6 Transition zone

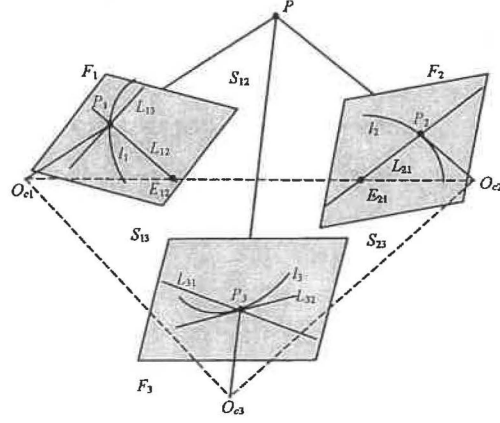


Figure 7 Image matching

In Figure 7 O_{ci} ($i=1\sim3$) are optical centers of three cameras. F_i is the image plane of camera i . l_i is the image of line stripe on image plane F_i . P_i is the projection of point P on F_i , which is the intersection point of PO_{ci} and F_i . P_1 , P_2 and P_3 are called homologous images. The plane formed by $PO_{ci}O_{cj}$ ($j=1\sim3, j\neq i$) is called epipolar plane S_{ij} . Intersection of epipolar plane S_{ij} with plane F_i forms epipolar line L_{ij} . L_{ij} and l_j are called conjugation epipolar lines. E_{ij} is the intersection point of the optical center line $O_{ci}O_{cj}$ with image plane F_i and called epipole. The homologous image P_2 of image P_1 on plane F_2 must be on epipolar line L_{21} . From another side it should be on image of line stripe l_2 . So it must be located at the intersection point P_2 of L_{21} and l_2 as shown in Figure 7. The homologous image P_3 of image P_1 on plane F_3 must be on epipolar line L_{31} . From another side it should be on image of line stripe l_3 . So it must be located at the intersection point P_3 of L_{31} and l_3 . In the mean time it should be also located on epipolar line L_{32} . Since all the images are subject to have certain errors for improving the accuracy and reliability of image matching the grey level similarity constraint is applied simultaneously. The grey level similarity of points P_1 , P_2 and P_3 is evaluated according to the following formulas [7]. First the average $\overline{f_i(u_i, v_i)}$ and standard deviation $\sigma(f_i)$ of the grey level of point P_i in a neighborhood area with $(2N+1)\times((2M+1)$ pixels are calculated.

$$\overline{f_i(u_i, v_i)} = \frac{\sum_{n=-N}^N \sum_{m=-M}^M f_i(u_{i+n}, v_{i+m})}{(2N+1)(2M+1)}, \quad \sigma(f_i) = \sqrt{\frac{\sum_{n=-N}^N \sum_{m=-M}^M f_i^2(u_{i+n}, v_{i+m})}{4NM} - \overline{f_i^2(u_i, v_i)}} \quad (15)$$

After that the correlation between the grey levels of points P_i and P_j $\text{Cor}(P_i, P_j)$ and similarity of three points $\text{Similarity}(P_1, P_2, P_3)$ are calculated.

$$\text{Cor}(P_i, P_j) = \frac{\sum_{n=-N}^N \sum_{m=-M}^M [f_i(u_{i+n}, v_{i+m}) - \overline{f_i(u_i, v_i)}] \times [f_j(u_{j+n}, v_{j+m}) - \overline{f_j(u_j, v_j)}]}{4NM\sigma(f_i)\sigma(f_j)} \quad (16)$$

$$\text{Similarity}(P_1, P_2, P_3) = \frac{1}{3}\text{Cor}(P_1, P_2) + \frac{1}{3}\text{Cor}(P_1, P_3) + \frac{1}{3}\text{Cor}(P_2, P_3) \quad (17)$$

The homologous images are searched in a defined neighborhood of points P_2 and P_3 .

Based on any two of homologous images among P_1 , P_2 and P_3 a point P_{ij} in space can be determined. The gravity center of the triangle form by P_{12} , P_{13} and P_{23} is taken as the position of point P .

8. Data reconstruction

Due to huge amount of sampled data a data reduction algorithm based on distance criterion is applied before data reconstruction [8]. A straight line is formed by two end points P_1 and P_n of the light stripe after image processing. A point P_m with maximum departure from line P_1P_n is found and distance δ from P_m to line P_1P_n is calculated. All points between P_1 and P_n will be ignored and replaced by a straight line P_1P_n if $\delta < \delta_0$, where δ_0 is the given

threshold. P_m will be kept for further data processing if $\delta > \delta_0$, and P_m will be used as the new end point. Two straight lines P_1P_m and P_mP_n are formed. The whole process repeats until all points on the line stripe will be processed.

Since only the NURBS meets the requirement defined by STEP and is applicable for reverse engineering an algorithm combining triangular Bezier patch modeling technique with NURBS modeling technique is developed. All the data points are projected to $x_wO_wy_w$ plane of the world coordinate system. There is a correspondence between point in space and projected point in case of monotonic convex or concave sculptured surface. The Delaunay triangular division and Bezier interpolation are applied to get a G^0 continuous Bezier surface. The projection of the reconstructed Bezier surface on $x_wO_wy_w$ plane is divided into grids to meet the requirement of NURBS modeling. NURBS interpolation is applied to get a G^2 continuous surface. Smoothing is carried out by adjusting the controlling points.

9. Experiments

For verifying the accuracy and feasibility of the developed probe some gage blocks, a cylinder and a turbine blade surface were measured. Experiments show that the trinocular probe enhances both accuracy and reliability of measurement in comparison with binocular one. An accuracy of 0.02 mm was achieved in the first prototype developed. Some data of gage block measurements are given in Table 1. The standard deviation in measuring a cylinder is 0.01mm.

Table 1 Results of gage block measurement

No. of gauge block surface	Nominal height of the block from the base surface (mm)	Measured height of the block from the base surface (mm)	Deviation from nominal value (mm)
1	2	1.9971	-0.0029
2	3	2.9922	-0.0078
3	5	4.9893	-0.0107

10. Acknowledgements

This study is financially supported by the National Natural Science Foundation of China (project No.50075064) and Ronghong Endowment of the United Technologies Corporation, USA. The authors would like to express their sincere appreciation to the National Natural Science Foundation of China and Ronghong Endowment of USA.

11. References

- [1] Werner A, et al. Reverse Engineering of Free-form Surface. Journal of Material Processing Technology, 1998, 76: 128~132
- [2] Saito K, et al. Non-contact 3-D Digitizing and Machining System for Free-form Surface. Annals of CIRP, 1991, 40 (1): 483~486
- [3] Umesh R D, Aggarwal J K. Binocular versus Trinocular Stereo. IEEE Intelligence Transportation Systems Conference Proceedings, 1990, (1):2045~2050
- [4] Tsai R Y. A Versatile Camera Calibration Technique for High-Accuracy 3D Machine Vision Metrology Using Off-the-Shelf TV Cameras and Lenses. IEEE Journal of Robotics and Automation, 1987, RA-3(4):323-344
- [5] Castleman K R. Digital Image processing, 1998, Prentice-Hall International, Inc.
- [6] Edward P L, Owen R. Subpixel Measurements Using a Moment-Based Edge Operator. IEEE Transactions on Pattern Analysis and Matching Intelligence, 1989, 11(12): 1293~1309
- [7] Elsayed E H. A 3-D Trinocular Active Vision System for Surface Reconstruction. PhD Thesis, 1992, University of Cairo
- [8] Chen Y H, Ng C T, Wang Y Z. Data Reduction in Integrated Reverse Engineering and Rapid Prototyping. International Journal of Computer Integrated Manufacturing, 1999, 12(2):97-103

Non-Contact Shape Measurements of Ultra-Lightweight X-Ray Optics

Theo Hadjimichael¹, David Content², Charlie Fleetwood¹ Eugene Waluschka²,
Geraldine Wright²,

1. Swales Aerospace, Beltsville, MD

2. Optics Branch, NASA Goddard Space Flight Center, Greenbelt, MD

1. Abstract

We are measuring the shape of thin glass optics under development for the soft x-ray telescope for the Constellation-X space observatory. Metrology on ultra-lightweight optics is often a difficult procedure because typical contact pressures on the optic distort its shape significantly. In order to achieve an accurate surface measurement, we are using non-contact metrology methods. We are developing the ability to create a three dimensional map of a lightweight x-ray optics using a single point non-contact probe. When fully automated, this technology will give us the ability to map and reduce data with as much speed and efficiency as the mirrors are able to be fabricated.

2. Introduction

The noted success of the Chandra x-ray telescope underscores the growing astronomical interest in x-ray sources such as black holes, supernovae, galaxy clusters, etc. The Constellation-X follow-on mission now under development [1] aims to collect many more x-ray photons from each source so as to allow x-ray spectroscopy. Our aim is a highly sensitive soft x-ray space observatory (0.25-10 keV energy, or ~6 to 0.1 nm wavelength range). Each of 4 identical co-pointed telescopes will be comprised of many nested thin (0.4 mm) shells of grazing incidence mirrors. Our group is a part of collaboration between GSFC, MIT, MSFC, and SAO developing the technologies required to fabricate, test, assemble, and align these telescopes.

This paper is a progress report on efforts to measure the shape of these optics at various points in the fabrication process and to compare them to the mandrels used to make them. Details of the fabrication process are available elsewhere [2]. For purposes of this paper, consider the optics to be 60° segments of cones with diameter ~500mm, cone angle ~1° or less, and length 20 cm, 0.4 mm thick.

3. Explanation and Integration of CMM Components

At Goddard we have a Moore Coordinate Measuring Machine (MCMM), model number 3, serial number M172. The MCMM has a lateral (x and y) axis resolution of 0.5 micron and a vertical (z) axis somewhat greater, 2.54 microns, as a stand-alone instrument. X-axis range is 457mm, y 279mm, and z 432mm. The whole instrument is on air vibration isolation pads and in a semi temperature controlled room.

In order to achieve the required measurement accuracy, we had to modify our original Moore Coordinate Measurement Machine. An Axiom 2/20 Laser Measurement System, developed by Zygo, has been retrofitted to the MCMM, replacing the dial gauges for each of the three axes. The Axiom 2\20 uses a simple helium-neon laser to interferometrically measure linear displacement. By attaching optics and receivers to each axis, we are able to keep track of distance traveled to a much higher degree of accuracy than the original Moore X, Y, and Z dials; we can achieve a maximum nominal resolution of 1.25 nanometers, updated at 7 to 13 megahertz. This data is sent to a computer, which can provide a number of storage and data manipulation options. In practice the resolution repeatability is poorer than this, presumably in part due to the limited environmental control; the best measurement repeatability we can achieve is 200 nm rms.

We have recently mounted a non-contact probe to the MCMM. The Microtrak 7000 Laser Displacement Sensor with MT-100-5 Sensor Head developed by MTI Instruments, Inc. uses a small helium-neon laser and triangulation techniques to display surface displacements across machined surfaces such as grooves, channels or step heights. It has a standoff distance of 25.4 mm, a resolution of 0.005 microns, and a linear range of 127 microns with a nominal spot size of 36 x 56 microns. We are using it to take many measurements across an entire part in order to gain a 3-D map of its surface. The data from this controller is interfaced into a LabView computer program written at Swales Aerospace along with the data from the Axiom 2/20 Laser Measurement System with multiple organizational and manipulation features.

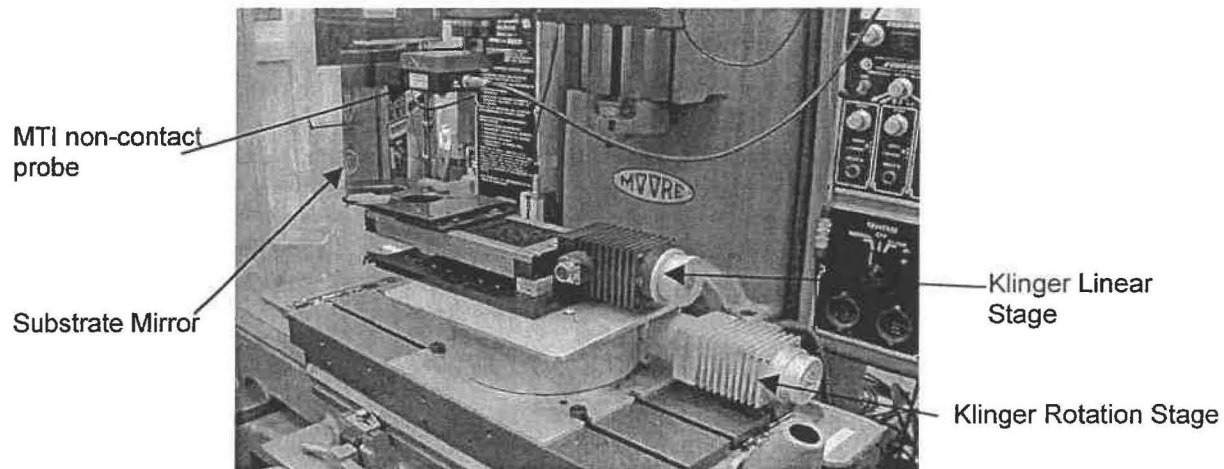


Figure 1: Moore CMM with non contact probe measuring large substrate on Klinger rotation and linear stages.

The final components added to the MCMM are a set of Klinger stepper motor linear and rotation stages (see figure 1). In order to gain the proper in-plane motion, i.e. radial motion, of the part to be measured with respect to the probe, this extra linear stage had to be added on top of the circular stage. The Klinger stages were chosen so that we could easily automate our system. The automation of these stages was also incorporated into the LabView program. The linear stage has a nominal resolution of 0.1 microns and the circular stage a resolution of 0.001 degrees. To summarize the newly modified CMM, these two Klinger stages are mounted atop one another to the X-Y stage of the MCMM. The MTI non-contact probe is mounted to the Z axis of the MCMM and the travel of each axis is measured by the Axiom 2/20 (see Figure 1). Each of the devices are being kept track by a simple LabView code.

4. Initial Measurement

Initial tests of the system began on a diamond turned flat mirror. The alignment procedure was simple; the mirror is aligned parallel to the motion plane of the probe by aligning the mirror normal to the non-contact probe to within the probe's maximum displacement range in the x-z plane. A total of 413 points were recorded in a 15mm x 25mm square area. A least squares fit in MathCad is used to fit a plane to these points with an standard deviation of the difference of the data and the fit (hereafter rms) value of 1.9 microns. Although we know that this particular test flat is better than 0.1 micron RMS (measured by a WYKO interferometer) the value was sufficient to that needed for the x-ray mirror shape determination. We moved on to measuring the Ultra-lightweight X-ray mirrors.

The next step was to try a 60 degree x 25 mm section of a diamond turned reference cone with a top radius of 89 mm and a half cone angle of 0.3 degrees. The part is known to be a straight right circular

cone by virtue of its fabrication method and prior work on the MCMM and other metrology. Alignment of the reference cone proved less simple along a curved surface as the non-contact probe becomes less reliable when trying to read at an incorrect incidence angle. We developed a process consisting of two stages: 1) mechanical alignment of the probe axis with respect to the axis of the rotation stage, and 2) iterative focus adjustment of the part by scanning through the full 60° angular range at a given focus position to test whether the probe stayed in its limited range throughout the scan. This process was repeated until the full 60 degrees of the test part could be read. The LabView code could be set to automatically take readings of all axes including rotation every 2 degrees for a total of 60 degrees and then return to its original position. As the Z-axis is not automated, at the end of each profile the z-axis is then moved to the next desired height (in the case of the reference cone every 1 mm) and the next angular profile is taken.

Once these measurements were taken and the process was proved to work, a Constellation X substrate was placed against the alignment posts and a 3-D map of the surface was obtained. The substrates have a midpoint diameter of approximately 489 mm. Alignment of the cone to within the probes tolerances is fairly difficult. If the bisector of the probe triangulation beam is not aligned normal to the curved surface of the cone, a reading can still be gained traveling inside or outside of the designated 25 mm standoff distance, depending to which side the part curves with respect to the input pupil. Also the size of the surface (45-60° x 200mm) creates a problem such that as we move along the z-axis and rotate about a fixed radius, the probe is no longer able to stay within its 127 micron readable range. This is compensated for by subtracting the probe displacement measurements from x-axis measurements taken by the Axiom 2/20. Thus, when the probe is about to move out of its range the x-axis on the MCMM can compensate and bring the probe back to within the required 25.4 ± 0.127 mm of the test part.

5. Data Analysis

The analysis of our data took part in two phases. First, raw axial and circumferential profile data were reduced using an Excel spreadsheet. Then using a combination of IDL and MathCad programming a 3-D rendering of the data points and a cone fitting routine were applied. Using Excel to fit the four sides of our data; a top and bottom circularity measurement and the two side axial measurements, we are able to both show good 2-D profiles and possible extraction of some information on how our part is misaligned. This misalignment analysis may allow us to retake our data for a better dataset with less error. The results of this data reduction are shown in Table 1 and Figures 2 and 3..

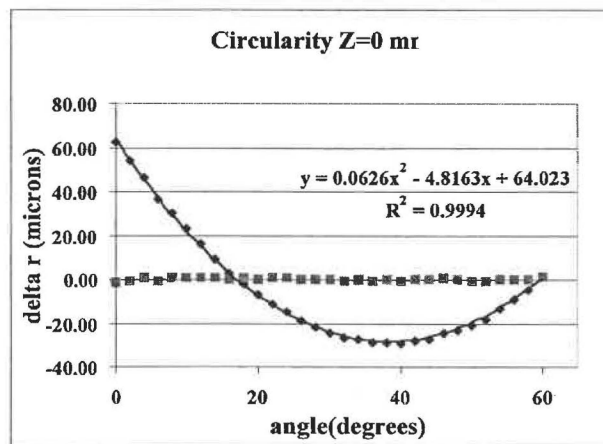


Figure 2: Circularity profile of reference cone, 2nd order fit.

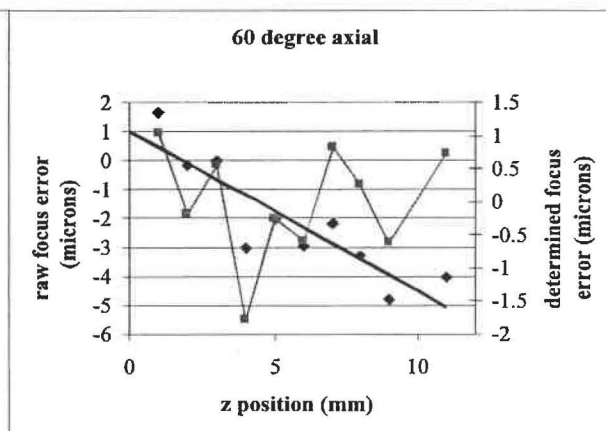


Figure 3: axial profile of reference cone, first order (tilt) removed

In both figures small diamonds represent the raw displacement data while the large triangles represent the subtracted data from the fitted curve. Preliminary repeatability tests on the axial and circularity profile of the reference cone appear adequate but more analysis needs to be done in order to confirm exactly how well it repeated. For each of the circularity measurements we are seeing rms values from 0.6 to 0.8 microns and for axial measurements approximately 1.3 micron. The axial measurements fit to first order lines gave rms values of 0.8 to 1.6 micron (see table 1). This same approach was then taken for the larger Constellation –X ultra-lightweight substrate mirrors. Again the axial measurements show rms values of 7 to 15 microns and circularity measurements of 2 to 3 microns (see table 1). The repeatability on the large substrate is harder to discern than with the reference cone. From a purely graphical standpoint the axial repeatability is poor while the repeatability on the circularity looks good. This may be a result of the much larger axial distance traversed on the large substrate, 100 mm, than on the reference cone, 9 mm. It will be necessary in the future to modify the test to take into account the changing radius as the height is traversed rather than compensating for the fact that the probe goes out of range by simply moving the test part closer and not changing the radius about which it rotates. This approach was fine for the reference cone as its change in radius with changing height remained in range of the non-contact probe.

		0° axial RMS(microns)	60° axial RMS(microns)
reference cone	test 1	1.6	0.9
	test 2	1.34	0.86
489s-90 Substrate	test 1	8.14	7.09
	test 2	2.64	2.56
		Z=0mm circularity RMS(microns)	Z=9(100) circularity RMS(microns)
reference cone	test 1	0.65	0.71
	test 2	0.65	0.79
489s-90 Substrate	test 1	2.65	3.2
	test 2	13.06	14.86

Table 1: Axial and Circularity RMS values in microns of the reference cone and Substrate tests.

In the next step in data reduction the raw data from the non-contact probe and Axiom 2/20 interferometer displacement devices were reconstructed from a Cylindrical (ρ , θ , Z) into a Cartesian coordinate system (X, Y, Z). This was accomplished by the addition of a nominal radius given by the known midpoint radius of the part in the case of the reference cone. For the case of the substrates the known mandrel midpoint radius, from which they were replicated, was used. This new Cartesian dataset was then brought into MathCad for reduction and graphic display. In each case we used a least squares method to fit the data. We used an iterative approach: 1) Allowing the dataset to move with 6 degrees of freedom (representing small remaining misalignments) in order to find its best fit to the known, fixed mandrel (reference) cone formula. This removes any misalignment of the dataset to the fixed coordinate system. Typical angular and linear misalignments were on the order of 0.2 degrees and 0.2 mm respectively. 2) The actual best fit cone was found again using a least squares approach and a comparison of known to actual cone formulas was made. The results of this hierarchical approach are summarized below (see table 2).

		Reference Cone test 1	Reference Cone Test 2	Substrate 489s-90 test 1	Substrate 489s-90 test 2
Measured Values	half-cone angle(degrees)	0.323	0.5201	1.71	1.91
	Initial Radius (mm)	89.23	89.21	243.72	244.05
	RMS (microns)	1.8	2.4	8.3	6.64
Mandrel Values	half-cone angle(degrees)	0.3	0.3	0.96	0.96
	Initial Radius (mm)	88.9	88.9	243.997	243.997

Table 2: Final MathCad test results and Comparison for Substrate and Reference Cone

6. Conclusion

Our results from our upgraded non-contact mode Moore CMM look promising. Some modifications still need to be made in our data taking procedure. For instance, on larger parts, allowing the radius to change with changing height and recording this change into our final LabView dataset. Also the least squares data reduction and hierarchic approach is possibly too simple. Looking at the results of this data reduction it seems that we are falling into local minima where the radius seems to be finding a close fit, but the half cone angles are evidently not well fit. We are looking into Global fitting techniques in order to correct for this. Finally we are moving towards a fully automated system in which not only will the Z-axis automated but our LabView code will be programmed to compensate for known radius changes and to be able to recognize when the non-contact probe is out of range and compensate appropriately.

Acknowledgements

David Colella, Mantec; Tammy Faulkner, Swales Aerospace; Tim Mengers, Swales Aerospace
Disclaimer: Mention of trade names or commercial products does not constitute endorsement or recommendation by NASA or by Swales Aerospace.

References

- [1] See the description of Constellation-X online at <http://constellation.gsfc.nasa.gov/>
- [2] W. W. Zhang, K. Chan, D. A. Content, R. Petre, P. J. Serlemitsos, T. T. Saha, Y. Soong, "Development of mirror segments for the Constellation-X Observatory," Proc. SPIE **4851**-58 (2002).

High Accuracy CMM Measurements of Large Silicon Spheres

John Stoup, Theodore Doiron

National Institute of Standards and Technology, Gaithersburg, MD

Abstract.

The NIST M48 coordinate measuring machine (CMM) was used to measure the average diameter of two precision, silicon spheres of nominal diameter near 93.6mm. A measurement technique was devised that took advantage of the specific strengths of the machine and the artifacts while restricting the influences derived from the machine's few weaknesses. This effort resulted in measurements with unprecedented accuracy and uncertainty levels for CMM style instruments. The results were confirmed through a blind comparison with another national measurement institute (NMI) that used special apparatus specifically designed for the measurement of these silicon spheres and employed very different measurement techniques. The standard uncertainty of the average diameter measurements was less than 20 nanometers. This paper will describe the measurement techniques along with the decision-making processes used to develop these specific methods. The measurement uncertainty of the measurements will also be rigorously examined.

1.0 Introduction.

The kilogram is the only remaining fundamental unit within the International System of Units which is defined in terms of a physical artifact, a Pt-Ir cylinder kept in the International Bureau of Weights and Measures (or BIPM) in Paris. There are several ongoing attempts to redefine the kilogram independent of the artifact along with other exploratory projects in the density field that are very closely related to the kilogram efforts. The preferred objects used for this work are finely polished single crystal silicon spheres with a mass of very near one kilogram. This results in a spherical diameter of about 93.6mm. The spheres are manufactured at the Australian Center for Precision Optics (APCO), a facility located within the Commonwealth Scientific and Industrial Research Organization (CSIRO); the national measurement institute of Australia. A typical APCO silicon sphere has roughness characteristics of 0.2 RMS and a sphericity of less than 50nm RMS. Measurements were recently performed at NIST on two APCO silicon spheres. The NIST measurement process was dramatically different in that it used commercially available measuring equipment and measurement methods. The NIST measurements were performed using the flexible, stylus-based Moore M48 coordinate measuring machine¹.

The machine is housed inside a specially built thermally controlled room. This room maintains a constant 40 % (± 2 %) and a constant 20.00 degree Celsius temperature (± 0.02 °C) within the volume of the room over a 24 hour timespan. The room has a quick air exchange rate and maintains a constant laminar flow from ceiling to floor. The indirect lighting fixtures are sealed and are kept at low light levels while air is moved through the fixtures and removed from the room to minimize any convection and radiant heating from the lights. Additional fans are used to reduce thermal gradients around the M48 table surface and under the cross bridge. These techniques result in thermal gradients of less than 10 millidegrees within the full 1000mm x 600mm x 300mm measurement volume of the machine. Constant temperature air is also pulled through the machine through several ducts to maintain constant temperature on the inside surfaces as well as the outside surfaces. The machine temperature environment is monitored through a series of 14 sensors placed in and around the machine. Index of refraction corrections are made to the laser outputs using state of the art pressure and temperature monitoring equipment.

Key to the exceptional performance of the M48 is the reproducibility of the error map. The map currently holds terms for the scale, pitch, yaw, and roll errors of each machine axis as well as the measured squareness and straightness motion errors of the axes. Mapping a machine like the M48 presents some unique problems. The exceptional raw motion accuracy of the M48 requires that the mapping exercise be performed independent of the machine controller supplied mapping options to increase the sensitivity of the corrections. The stability of the machine error map is quite good. Because the machine has not moved from its floor position for over 14 years, the advantages gained by the M48 physical design, room control, and footprint stability allow the map to remain stable for long periods of time.

2.0 The Measurement Method.

The development of the CMM measurement method for the silicon spheres was complex. The inherent flexibility built into a CMM becomes a distinct disadvantage when trying to achieve accuracy at a level of several nanometers. It was evident that to achieve the accuracy requirements of the spheres it would require a very unique approach with some novel measurement techniques. The final measurement plan naturally separated into two distinct paths of focus. First, the strengths of the machine, such as the smooth mechanical motions, the room environment, and the repeatability characteristics, were exploited as much as possible. Historical measurement data has proven that the M48 performs very consistently and is very repeatable over long periods of time. The machine also behaves very predictably as a result of internal heating effects during these long measurement runs. Second, any unaddressed and multi-axial errors should have their influences on the measurement results minimized as much as possible. Historically, the M48 has excelled during 1D comparison-style operations where the flexibility of the machine is severely restricted. The challenge for the sphere measurement method was to approach this ideal as closely as possible.

Three stainless steel spheres were selected as master artifacts and calibrated along a specific two-point diameter using the NIST Strang Interferometer². The nominal sizes of the stainless steel master spheres, 25.4mm, 19.05mm, and 12.7mm, were selected for several reasons. The spheres needed to be large enough so that they could be rigidly mounted on the CMM work-surface using existing mounting fixtures. These fixtures hold the spheres in a kinematic, 3-ball magnetic mount that allows unobstructed access to the equator of the spheres. This configuration was optimized for using 25mm diameter spheres and was modified to accept smaller spheres while maintaining a rigid stability during touch probe measurements. Using multiple mastering artifacts also facilitates the sampling of the unmapped CMM positioning errors during the silicon sphere comparison process.

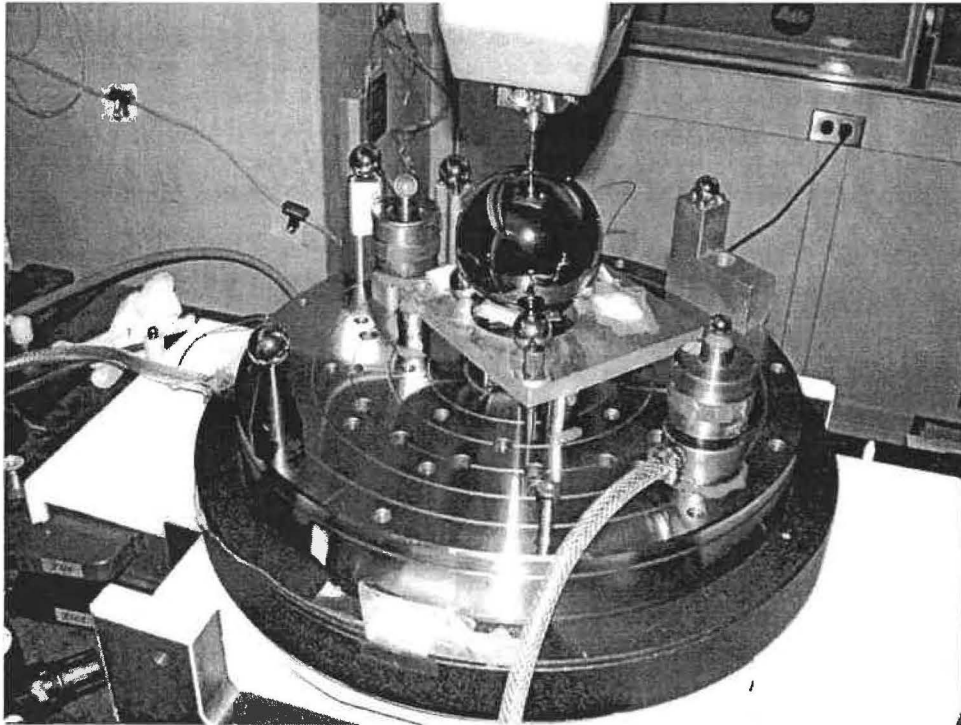


Figure 1. The artifact measurement setup on the rotary table.

A novel technique was devised to facilitate the requirement of 1-D data collection and is shown in Figure 1. The probe deflection sphere, the three stainless steel master spheres, and the silicon sphere were mounted on a precision rotary table interfaced to the CMM machine controller which allowed for the rotary table to be positioned and controlled automatically during the data collection. The silicon sphere was

specifically mounted directly central to the rotation axis of the table. This assured that when the table was rotated to predetermined angular positions, the two-point diameter measurements of the silicon sphere were still performed directly along the proper central axis of the sphere without having to redefine the sphere's central location. The mounting technique was designed so the sphere could be removed and replaced without damage to the delicate surface. The sphere was set on a cork pad on the top of a precision jack that could be slowly lowered and centered so the silicon sphere could be directed to make contact with the three kinematic mounting points at the same time. This minimized the impact to the sphere and the possibility of damage to the surface. The three master spheres were positioned in different locations around the rotary table such that the calibrated diameters were located parallel to the machine X-axis. This setup allowed for these initial master sphere locations to be relocated easily if the rotary table moved to other angular positions and could be redundantly re-measured at the exact location identified in the initial interferometric measurements on the Strang monochromatic viewer.

The unique measurement procedure combined redundancy and repeatability into a thermal drift eliminating data collection design. Following the initialization of the probe bending and deflection variables, the three stainless steel master sphere locations were determined and two-point diameter measurements were repeatedly collected for each along the machine X-axis. The silicon sphere location was then determined and a two-point diameter was also repeatedly measured along the machine X-axis. The silicon sphere was then rotated at 15-degree intervals and subsequent two-point diameter measurements were repeatedly collected along the same probe and machine X-axis at these new radial positions. Following each 15-degree interval, silicon sphere diameter measurement, the rotary table was moved to the original position and the three master sphere two-point diameters were again re-measured. This process was run through a 180-degree rotation of the silicon sphere then run in the reverse direction to provide a thermal drift elimination technique to the data set. The silicon sphere data collected during any single measurement sequence resulted in basically a 13-point average diameter around a single cross-sectional plane of the sphere. The repetitive measurements of the master spheres provided a good averaging of the master sphere values and brought any probe repeatability and drift concerns along with any machine repositioning inaccuracy into the random fluctuations of the data set.

The final very important advantage to the rotary table setup was for sampling any uncorrected CMM positioning errors and silicon sphere roundness errors. Concentrating all measurement artifacts onto the rotary table surface allowed for the easy repositioning of the whole rotary table assembly on the CMM table. The rotary table was moved to nine locations around the CMM work surface thereby sampling any positional dependent systematic errors into the random fluctuations of the data set. The control program only required the new locations of the spheres within the work volume to be redefined to the CMM controller resulting in a very efficient process. The silicon sphere was also rotated in the mount through the three orthogonal axes in addition to other random positions and measured with the rotary table at a fixed position. These tests result in constant machine error behavior and the effects of sphere geometry were independently derived.

3.0 The Measurement Data.

The data analysis for the first silicon sphere indicated an average diameter of 93.611471 mm. The result from the independent measurements performed at CSIRO in Australia was 93.611461 mm. The NIST measurements were 10 nm larger.

The data analysis for the second silicon sphere indicated an average diameter of 93.610218 mm. The result from the independent measurements performed at CSIRO in Australia was 93.610215 mm. The NIST measurements were 3 nm larger.

The agreement between the NIST and CSIRO measurements was excellent.

4.0 Measurement Uncertainty Calculations.

The difficult task of calculating the uncertainty for a coordinate measuring machine measurement can be streamlined for 1-D measurements performed along a single axis of the instrument. Most of the complicated three-dimensional errors relating to instrument positioning, datum generation, and probe-based coordinate errors are reduced to only single axis effects that can be much easily measured. In addition, by using the CMM as a comparator rather than an absolute measuring instrument, the error budget can be reduced to a manageable collection of error sources.

The uncertainty components are compiled in the Uncertainty Budget Table 1.

Error Component	Standard Uncertainty (k=1) in Nanometers	Brief Description
Master Artifacts	9.7	Uncertainty for single-point diameter measurements on the Strang Interferometer.
CMM Laser Scale Index of Refraction Error	0.06 L	Uncertainty in the Edlen Equation, laser wavelength, beampath temp., pressure, and humidity for index of refraction calculations.
CMM Scale Mastering Error	0.100 L	Limitation by the combination of historical performance verification and long end standard artifact uncertainty.
Elastic Deformation Predictions	5.8	Rectangular distribution of a ± 10 nm experimentally determined performance vs. predicted elastic behavior.
CMM Uncorrected Positional Errors	8.3	Multiple technique, experimentally determined performance of 25 nm reduced by $\sqrt{9}$ where 9 is the number of independent machine positions sampled in the average calculations.
Silicon Sphere Form Errors	5.1	Diameter measurements at six random planar positions. The 25 nm range was reduced by $\sqrt{6}$ term for the average calculations.
CMM Positioning and Probe Repeatability	Neg.	Error source adequately sampled in CMM positional error term.
Probe Mastering Error	Neg.	Either negligible for 1-D measurements or previously sampled.
Silicon Sphere Centering Error	Neg.	Total run-out contained to less than 3 μm results in negligible effect.
Surface Finish Effects	Neg.	Si sphere $R_a = 0.2$ nm, master spheres $R_a = 25$ nm. Triggering force results in predictable bulk material elastic behavior range.
Silicon Sphere CTE Uncertainty	0.5	10% unc. in bulk material property, meas. temp. of 20.02°C. $u(F) = (0.1)(2.6 \text{ ppm/}^\circ\text{C})(93.5\text{mm})(20.00^\circ\text{C} - 20.02^\circ\text{C})$
Master Spheres CTE Uncertainty	0.4	10% unc. in bulk material property, meas. temp. of 20.02°C. $u(G) = (0.1)(10.5 \text{ ppm/}^\circ\text{C})(19.05\text{mm})(20.00^\circ\text{C} - 20.02^\circ\text{C})$
Thermal Gradients	1.2	5 millidegree gradients measured in setup area. $U(H) = (.005^\circ\text{C})(2.6 \text{ ppm/}^\circ\text{C})(93.5\text{mm})$

Table 1. Silicon sphere measurement uncertainty budget.

Combining these terms gives a combined standard uncertainty of ± 18.0 nm.

This results in an expanded uncertainty using a coverage factor of $k=2$ for the average diameter measurement of the silicon sphere of ± 36 nm. This is an outstanding result for a CMM style measurement.

5.0 Conclusions

The performance of the NIST M48 Coordinate Measuring Machine in the average diameter measurements of two exceptionally fine 93.6mm silicon spheres was outstanding. The M48 measurements agreed very well with independent measurements using very specialized equipment and very different techniques. The unprecedented quality of the artifact's geometry and surface finish allowed for a rigorous analysis of some very small and difficult to isolate measurement uncertainty sources in the operation of the M48 CMM. This analysis combined with the restricted design of the measurement methods and the inherent accuracy of the M48 resulted in measurements with a very low measurement uncertainty. It is expected that other current measurement requirements using the M48 CMM, such as large 2D gridplates and pressure piston and cylinder combinations will immediately benefit from this work. Measurement uncertainties for these and other measurements using the M48 CMM will be reduced based on that information learned about the very fine positional and reproducible motion accuracies of the machine.

6.0 References

1. Trade names and company products are mentioned in the text to specify adequately the equipment and procedures used. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.
2. Stoup, J.R., Faust, B., Doiron, T.: Minimizing Errors in Phase Change Correction Measurements for Gage Blocks using a Spherical Contact Technique. SPIE Proceedings - Recent Developments in Optical Gauge Block Metrology, San Diego, pages 162-163, 1998.

Author Index

Abackerly, Alvaro J.	51	Ogura, Ichiro	74
Baldwin, Jon M.	51	Okazaki, Yuichi	74
Bergmans, R. H.	39	Pan, Zengxi	17
Beutel, Dean E.	9	Parks, Robert E.	3
Bieri, Marco	69	Pereira, Paulo H.	9
Borchardt, Bruce R.	51	Peterson, John E.	43
Bottinelli, Stefano	69	Phillips, Steven D.	51
Breguet, Jean-Marc	69	Polini, W.	57
Caliò, Franca	26	Qiu, Zurong	78
Chang, David W.	43	Rasella, Marco	26, 57
Clavel, Reymond	69	Rasnack, William H.	51
Content, David	84	Rosielle, P. C. J. N.	39
Cui, Hongliang	17	Ruijl, Theo A. M.	33
Devitt, Andrew J.	49	Salsbury, James G.	63
Doiron, Theodore D.	89	Sawyer, D.	51
Fan, Yuming	78	Schellekens, Pieter H. J.	39
Fleetwood, Charles	84	Shakarji, Craig M.	51
Fracheboud, Maurice	69	Spaan, H. A. M.	39
Gleason Jr., Eugene A.	15	Spence, Allan D.	43
Guo, Jingbin	78	Stoup, John R.	89
Hadjimichael, Theo	84	Summerhays, Kim D.	51
Harris, John O.	43	Thalmann, Rudolf	69
Henke, Michael P.	51	Thomas, Paul D.	21
Henke, Richard P.	51	van Eijk, Jan	33
Heslip, Joe	43	van Seggelen, J. K.	39
Kuhn, W. P.	3	Waluschka, Eugene	84
Li, Xingfei	78	Wright, Geraldine	84
Li, Zhen	78	Wu, Peng	43
Liu, Zheng	78	Zhang, Guoxiong	78
Meli, Felix	69	Zhang, Hongwei	78
Miglio, Edie	26	Zhao, Xiao Song	78
Moroni, Giovanni	26, 57	Zhu, Zhenqi	17
Murray, Pamela	51		



VOLUME 29

ISBN 1-887706-31-3